3.0 Air Pollution Control Techniques

The flue gas from hazardous waste burning incinerators, cement kilns, lightweight aggregate kilns, boilers, and halogen acid furnaces can contain a variety of contaminants, including particulate matter (PM), acid gases (such as SO_2, HCl, HF, etc.), metals (such as mercury, cadmium, lead, etc.), and trace organics. This chapter presents information on the design, performance, process monitoring requirements, and typical inspection and maintenance procedures for maintaining proper operation of common air pollution control devices designed for the removal of these contaminants from the flue gas.

Air pollution control systems used by the various hazardous waste combustor classes include, as discussed previously in Chapter 2:

- Cement kilns – Electrostatic precipitators (ESPs) and fabric filters (FFs) for particulate (containing condensed metals and organics) control.
- Lightweight aggregate kilns – FFs for particulate control, sometimes in combination with dry scrubbing and wet scrubbing for acid gas control.
- Incinerators – A variety of different air pollution control systems. These include:
  - Dry scrubbing in combination with dry particulate control with FFs or ESPs ("dry" air pollution control systems).
  - FFs or ESPs (dry PM control devices) followed by wet scrubbing ("wet/dry hybrid" air pollution control systems).
  - Wet scrubbing systems for both PM and acid gas control, including various different combinations of wet scrubbers such as ionizing wet scrubbers, wet ESPs, venturi scrubbers, packed beds, and spray towers.
- Solid fuel boilers -- FF or ESPs.
- Liquid fuel boilers – Most are uncontrolled; some use FF and wet scrubbers.
- Halogen acid and sulfuric acid recovery furnaces – Multiple stages of wet scrubbers.

The following air pollution control techniques that are used on hazardous waste burning combustors are discussed:

- Cyclones -- Used for coarse particulate removal.
- Fabric filters -- Used for coarse and fine particulate removal.
- Electrostatic precipitators -- Used for coarse and fine particulate removal.

- Venturi scrubbers -- Used for both particulate and acid gas control.

- Wet scrubbers -- Used primarily for acid gas control. Ionizing wet scrubbers control particulate matter as well as acid gases.

- Spray dryers and dry scrubbers -- Used for acid gas control.

- Hybrid wet/dry scrubbing systems -- Used for both acid gas and particulate control.

- Flue gas cooling -- Includes techniques such as water quench, air dilution, waste heat boilers, or heat exchangers.

- Other metals control techniques -- Including activated carbon used for volatile metals and organics control, earth-based sorbents for semi-volatile metals control, and specific mercury control techniques including selenium coated filters, sodium sulfide injection, and mercury scrubbers.

- Catalytic oxidation -- Used for organics control.

- Sulfur-based control -- Used for organics control, in particular PCDD/PCDF.

Also discussed are the typical integrations of various individual air pollution control devices that are used, including “dry”, “wet”, and “hybrid wet/dry” scrubbing systems.

3.1 Cyclones

Cyclones are typically incorporated as a pre-filtering process for removing large particles from the flue gas. Cyclones can operate at relatively high temperatures and function without moving parts, making operation simple. The cyclone chamber provides angular (swirling) gas flow which causes the suspended particles to accelerate toward the chamber walls. Particles, being denser than gas, separate from the gas stream and impact the cyclone chamber walls. The cyclones are erected vertically and the particles fall under gravity to the collection hopper.

3.1.1 Design Principles

The cyclone device is typically positioned immediately downstream of the primary combustion chamber. The cyclone’s service environment is dependent on its construction material. Cyclones can be constructed to withstand harsh environments such as extreme weather conditions and high temperatures since they have no moving parts.

The cyclone is typically a vertically erected conical or cylindrical shaped chamber which receives particle laden flue gas in the upper chamber region, as shown in Figure 3-1. The gas enters either tangentially or axially in a downward spiral path around the chamber walls. The spiraling motion causes the particles in the gas flow to accelerate to the chamber walls, where their momentum causes them to separate and fall out of the gas stream. The particles drop to the bottom of the cyclone by gravity and downward motion of the gas. The particles fall into the collection hoppers and are removed by an ash removal system. The cleaned gas still carries significant levels of fine particulate which remain suspended in the flow due to their airborne characteristics. The treated gas reverses direction at the bottom of the chamber and returns up the center of the chamber and exits out the top.

3.1.2 Performance

Cyclone removal efficiency is dependent on the gas velocity, rate of change of gas direction, and the particle size distribution, density, and composition. The main limitation of the cyclone is the inability to effectively remove small particles less than 5 µm in diameter. For small particles, the inertial separating force (particle momentum) is low and the particles are more prone to remain suspended in the gas stream.

The removal efficiency of a cyclone can be improved by increasing the swirling velocity of the gas, which increases the inertial separating force or particle momentum. This is effectively accomplished by reducing the diameter of the cyclone chamber or increasing the gas flow rate. Cyclone performance is affected by gas flow rate, since this affects the swirling velocity in the cyclone. Cyclone efficiency is relatively insensitive to dust loading, and in fact, the efficiency can increase with higher loading due to particle interactions.

Cyclone efficiency is generally poor compared with the efficiency of ESPs and FFs. Cyclone efficiency is less than 20% for sub-micron particulate. Efficiency increases with particle size, typically ranging from 5% for 0.5 µm particles to 50% for 3 µm particles.

3.1.3 Process Monitoring

The pressure drop and inlet gas temperature are monitored to assure proper operation. The pressure drop is monitored so that any tendency of the cyclone to plug can be signaled by high pressure drop. Also, leaks and cracks in the cyclone can be detected by reduced pressure drop. Pressure drop is also a function of gas flow and may be used as an indicator of capture efficiency. Generally, efficiency increases with higher pressure (i.e., higher gas flow). Monitoring of the inlet gas temperature may be required, depending on the cyclone's application and construction material, to operate above the acid dew point and avoid corrosive conditions.

3.1.4 Inspection and Maintenance

Cyclones have minimal maintenance requirements due to the lack of moving parts. Cyclone wall corrosion, leakage, particle deposits and plugging should be regularly checked. Life expectancy of cyclones is long and is only limited by material corrosion, erosion and thermal stresses and cracking. Overall, the cyclone requires very little routine maintenance and maintenance is typically done off-line in a non-hostile environment.

3.2 Fabric Filters

Fabric filters, also commonly known as baghouses, are used to remove gas suspended particles much like the filtration device on a vacuum cleaner. The FF is utilized in relatively low temperature environments (typically 250 to 450°F), but always above the dew point of water and common acid gases. The particle laden gas stream enters the FF chamber and passes through vertically suspended filter bags. Particles in the flue gas are collected on the filters. Particle build-up is periodically removed from the filters by one of a variety of methods. The collected particles fall to a collection hopper situated below the filter bags. General fabric filter attributes include:

- High particulate matter capture efficiency (including fine particulate).
- Capture efficiency is relatively independent of particle characteristics.
- Monitoring, inspection, and maintenance procedures are fairly simple.

3.2.1 Design Principles

Fabric filters are used to remove suspended particles from flue gas by capturing the particles on the surface of a porous fabric. Particle laden gas enters the collection device and passes through an array of cylindrical filtering bags which retain the particles; and the clean gas exits through the outlet duct. The design of the FF system slows the gas velocity and evenly distributes the gas to all the filter bags. Particles collect on the filters and form a dust cake on the surface of the filters. As the dust layer builds, it becomes more difficult for particles to penetrate. This increases both the pressure drop across the filters and the particulate collection efficiency. It is actually the dust cake which achieves the high collection efficiency. For this reason, unless the filters are preconditioned (i.e., an artificial filter cake is built-up) prior to operation, filter efficiency is lowest at start-up and immediately after the bags are cleaned.

Fabric filters are usually externally heated and/or insulated to ensure that the device remains above the minimum required operating temperature (typically greater than 250°F) to prevent condensation which can plug and corrode the filter bags. This is especially important during start-up and shutdown operations, when temperatures are likely to drop below the gas dew point. A FF's maximum operating temperature is limited by the working temperature of the fabric. For many common filtering fabrics, the maximum operating temperature is below 500°F. Fabric filters are equipped with spark arresters upstream to prevent fugitive sparks and hot flyash from burning the filters.

Fabric filters are most effective at collecting particles when coated with dust, however, too high a coating will create a high pressure drop across the filter. The pressure drop across the FF is an important parameter since it relates directly to energy cost for the induced draft fan. Typical differential pressures for FFs are 1 to 6 in. H_2O. The filters need to be cleaned periodically. When removing the dust build-up, it is important not to remove too much dust cake or else excessive dust leakage will occur while fresh cake develops. There are four principal types of cleaning systems: pulse jet, reverse gas, shaker, and sonic.

The pulse jet system utilizes high pressure air to clean the filters, as shown in Figure 3-2. The high pressure air inflates the bags, cracking the external dust cake. When the air is removed, the bags return to their original shape and the dust cakes drop into the collection hopper. Pulse jet systems can be cleaned while on-line, allowing continuous operation of the unit. Filters can be maintained from outside the collector, which allows the maintenance to be performed in a clean, safe environment. This vigorous cleaning technique tends to limit filter bag life.

In reverse air systems, the dirty gas enters the FF and passes from the interior to the exterior of the bags, as shown in Figure 3-3. The FF must be divided into modules which are taken off-line during cleaning. Low pressure air is introduced from the exterior of the bags, collapsing the bags and cracking the interior dust cake which falls to the collection hopper. The cleaning is accomplished with relatively low air pressure, resulting in maximum bag life. This method is preferred for easily damaged fabrics.

Shaker systems, shown in Figure 3-4, move the tops of the bags in a circular path, causing a wave motion through the bag length. This causes the dust to crack and fall to the hopper. Bags must have high abrasion resistance for this cleaning technique. In addition, individual bags must be taken off-line for the cleaning process.

Sonic cleaning, if used, usually augments another cleaning method. Sonic energy is introduced into the filtering device. The sonic waves generate acceleration forces that tend to separate the dust from the fabric.

Fabrics used for the filter bags are usually woven with relatively large openings in excess of 50 µm in diameter. Fiber types include natural fibers such as cotton or wool (not often used), and synthetic fibers such as nylon, acrylic, Dacron, Teflon, Nomex, Polyproplene, Goretex, and fiberglass. The synthetic fibers are typically resistant to moisture and acid/alkali components in the flue gas, however they have limited operating temperatures, typically around 500°F. The fibers may be either woven or felted. Woven fibers have a definite pattern, while felted fibers are randomly compressed into a dense mat. Newly developed ceramic and metal fiber bags have improved temperature resistance (greater than 1,000°F operations) and increased structural durability compared with conventional fabric media. The selection of the fiber bag material and construction is important to FF performance. Deciding factors for fabric selection include:

- Temperature -- Ability to withstand maximum continuous service temperature, and temperature surges. For typical fiberglass or Teflon bags, the maximum rating is about 500°F. New ceramic fibers are being developed that are able to withstand a much higher temperature level.

- Corrosion resistance -- Ability to resist degradation from acids, alkalis, solvents, or oxidizing agents.

- Hydrolysis -- Ability to handle effects of humidity. High moisture can cause blinding of the fabric.

- Dimensional stability -- Ability to tolerate shrinking and stretching fabric.

- <u>Fabric mechanical strength</u> -- Ability to withstand the structural demands exerted on the fabric by the gas flow and cleaning system.

3.2.2 <u>Performance</u>

Fabric filters are very efficient at removal of particles of all sizes. Fabric filter collection is relatively insensitive to (independent of) inlet mass loading. Three primary mechanisms are responsible for particulate capture on a relatively clean fabric: inertial impaction, direct interception, and Brownian diffusion. Both inertial impaction and direct interception are associated with relatively large particles, whereas Brownian diffusion is associated with smaller submicron particles. As discussed above, after a period of operation, a cake forms on the fabric surface, and "sieving" becomes a dominant collection mechanism. Sieving occurs when the particle is too large to pass through the surface cake which has built up on the fabric. Emissions of particulate through a fabric filter are due to particulate seepage through the dust cake and fabric, gas flow through gaps or tears in the fabric, and gas flow between gaps between the bags and the tubesheet. Due to these mechanisms, the particle size distribution of the particulate escaping the fabric filter has been shown to be similar to that in the inlet gas stream. Particle leakage through a fabric cake occurs due to the cake build up process:

- Individual particles strike edges of pores and form chains that bridge across the pores.

- As more and more pores become covered with cake, the gas velocity through the remaining pores increases significantly.

- The large gas velocity through the uncovered pores prevents the pores from being bridged.

- These uncovered pores become leakage points.

Fabric filter efficiencies can range between 99 and 99.99% for particle sizes as low as 0.1 µm. Particle capture is relatively insensitive to particle and dust physical characteristics such as particle resistivity and dust loading. Efficiency decreases as the air-to-cloth ratio increases as gas velocity rises. Air-to-cloth ratio is a ratio of the gas volume flow rate to the filter surface area and is a measure of the superficial gas velocity through the filter. Typical air-to-cloth ratios range from 3 to 5 $acfm/ft^2$, with lower air-to-cloth ratios of 2 $acfm/ft^2$ providing improved performance. Particle capture efficiency is also dependent on the frequency of bag cleaning, cake build-up, and fabric type and weave, as well as on the physical condition of the bags.

Factors which specifically affect the efficiency of a baghouse include:

- Holes and tears in the bag and fabric abrasion mainly due to too vigorous a cleaning cycle.
- Chemical attack of the fabric.
- Inadequate cake buildup.
- Thermal degradation of the bag fabric.

- Gas-to-cloth ratio (superficial flue gas velocity).
- Frequency of cleaning.
- Fabric specifications (i.e., fabric type and weave).

Fabric filter technology has made significant advances with the improvement in FF bag materials. As a result, FFs are quickly becoming a preferred APCD, especially since ash effluent is dry and does not require the handling and disposal processes of liquid waste. Recently developed techniques to improved FF collection efficiency that have been demonstrated include:

- Use of electrostatically enhanced filters; shown to have higher collection efficiency, lower pressure drops, and lower lifetime costs compared with conventional units. This technique is still in the design and development stage.

- Use of a fabric material made of polytetrafluoroethylene (PFTE) membrane. The PTFE has a smaller pore size compared with conventional felt fabrics, resulting in increased particulate matter collection. Levels below 0.001 gr/dscf have been demonstrated.

- Flue gas conditioning with ammonia and SO_3 has been shown to improve FF collection efficiency by increasing particulate cohesivity which improves the pore bridging ability, leading to reduced direct particle penetration. It also enhances the ability of the particulate to remain in place once caught, reducing the indirect penetration loses.

3.2.3 Upgrade Options

Procedures to improve existing FF performance include:

- Replacing the existing FF unit with a larger unit to reduce air-to-cloth ratio.

- Adding to the existing FF a parallel FF and thereby reducing the air-to-cloth ratio.

- Upgrading the existing FF material to higher performance filtering materials, and/or the use of precoating agents. This option typically represents the least costly upgrade procedure.

3.2.4 Process Monitoring

FF performance is directly monitored with “bag-leak detector” systems which provide a real-time indication of PM emissions levels. Bag leak detectors can include systems using triboelectric, lightscattering, or beta-gauge based PM CEMSs.

Fabric filter operations are also monitored by flue gas inlet temperature, gas flow rate, and pressure drop across the system. The baghouse temperature must be maintained above the acid condensation point in order to reduce corrosion and fabric wear. This is most important during system start-up and shutdown conditions. If acid deposition occurs after shutdown, the acid moisture will settle on the fabric and eventually leave behind a residue which may contribute to the brittleness of the bags and cause failure when put into operation again. An abnormally high pressure drop can signify that bags are binding or plugging, gas flow is excessive, or fabric cleaning is inadequate. Low pressure drop signifies possible filter holes and leakage, leakage between the bag and bag supports, or inadequate dust cake formation.

3.2.5 Inspection and Maintenance

Fabric filters are relatively simple to operate and require minimal maintenance and repair. However, they require frequent routine inspection and maintenance. Several FF inspections and maintenance items are required on a daily and weekly basis. Filter bags require periodic inspection for correct tensioning and conditions such as tears, holes due to abrasion, and dust accumulation on the surface. The typical filter bag life is as much as 10 years using reverse air cleaning, but this can be reduced to 2 years for improperly operated systems. Filter bags are fragile and prone to hole formation if not handled carefully.

Bag hole location can be detected using fluorescent powders. The powder is injected into the inlet of the FF to inspect for leaks. Leaks are detected by inspection for the powder on the clean side of the bag using ultraviolet light.

3.3 Electrostatic Precipitators

Electrostatic precipitators (ESPs) are remove particulate matter from flue gases by applying a charge to the particles, and then collecting the charged particles on oppositely charged collection plates. Electrostatic precipitators are available in a variety of designs and can operate in a dry or wet mode and in hot or cold gas conditions. General ESP attributes include:

- Relatively high PM capture efficiency.
- Lowest capture occurs with 0.1 to 1 µm particles.
- Extensive monitoring requirements.
- Automatic controls.
- Low routine maintenance.
- Low pressure drop.

3.3.1 Design Principles

Electrostatic precipitation is a process by which gas suspended particles are electrically charged and passed through an electric field which propels the charged particles towards collecting plates, as shown in Figure 3-5. The charged particles stick to the plates, and periodically a rapping (impact) mechanism dislodges the collected particles from the plates. The dislodged particles drop into the collection hopper for removal.

In the particle charging step, particles in the gas stream are charged by the development of a current of negative ions generated from a high-voltage corona discharge. The corona is established between an active electrode (usually a fine wire or plate of negative polarity) maintained at a high voltage, and a smooth cylindrical or plate electrode at ground potential. The corona ionizes the flue gas as it passes around the electrode, forming a large number of ions in the region near the electrode surface. Negative ions are attracted to the ground pipe or plate. Particles passing through the corona field are subjected to intense bombardment by the negative ions and become charged.

The negatively charged particles are electrically attracted to the grounded collection surface. The particle "migration velocity" toward the collection surface, which is influenced by the particle diameter, particle charge, and collecting field intensity, typically ranges from about 0.1 to 3 ft/sec.

Electrostatic precipitators can be found in both high and low temperature applications – with an upper temperature limit of about 1,300°F down to the condensation point of flue gas constituents of around 200°F. Precipitators are commonly designed for either hot- or cold-side treatment. Hot-side precipitators have larger collecting plate areas and are constructed of suitable steels to handle continuous high temperature operation. The "cold-side" categorization refers to the ESPs operating at gas temperatures below 500°F.

The general configuration of an ESP is a wire (or rod) discharge electrode positioned at an equal distance between two collecting plates. The electrostatic precipitator casing houses many passages of parallel collecting plates with wires (or rods) suspended at regular intervals through the passage. The plates are further compartmentalized into fields, with each field typically energized by its own set of power supplies. A negative high-voltage direct-current power is applied to the discharge electrodes, and the collecting plates are grounded. The high-voltage direct-current power produces a corona in the wire-to-plate spacing by ionizing the gas. The corona then creates an avalanche of negative ions traveling from the negative discharge electrode to the grounded collecting plates. Suspended particles passing through the wire-to-plate spacing are bombarded by negative ions and become charged. The high voltage electricity produces an electric field between the wire and the plate which provides the electromotive force to attract the charged particles to the collecting plates.

Electrostatic precipitators can be classified into three types: tubular, wire-to-plate, and flat plate. A wire-to-plate type ESP is shown in Figure 3-6. It consists of parallel plates of sheet metal collection surfaces with wire electrodes hanging between the plates. Flat plate ESPs, as shown in Figure 3-7, differ from wire-to-plate types in that the negative electrode consist of a flat plate rather than a wire. The plates increase the electric field used to collect the particles, and provide increased surface collection area. However, a flat plate ESP operates with little or no corona, which leads to large rapping losses, especially if the flue gas velocity is high. The tubular type, shown in Figure 3-8, consists of an array of tubes, round or multi-sided, which act as the collection surface, with a discharge electrode located in the center of each tube.

Also, there are two typical arrangements of the electrodes used in the ESP: single-stage or two-stage, as shown in Figure 3-6. In the single stage arrangement, the discharge and collecting electrodes are located in the same chamber. In the two stage arrangement, the discharge electrodes are placed in the first chamber, where particulate charging is accomplished.

Collection electrodes are placed in a second chamber located downstream of the first chamber. Particles are removed from the gas in the second chamber.

The following process characteristics dictate the specific ESP design:

- Gas volume flow rate.
- Particle loading.
- Gas temperature.
- Particle size distribution.
- Particle composition.

To accommodate these process characteristics, the following physical and electrical characteristics of an ESP may be varied:

- Number of fields.
- Number of passages per field.
- Wire-to-plate spacing.
- Collection plate surface area.
- Wire (or rod) diameter.
- Aspect ratio (length to height).
- Maximum secondary voltage.
- Maximum secondary current.
- Number of sparks per minute.

The charged particles which accumulate on the collecting surfaces must be periodically dislodged. Dislodging the collected particle layer is accomplished in several ways using either mechanical rapping devices or water for wet ESPs as discussed in a following section. Typically, dry electrostatic precipitators utilize mechanical rapping devices which strike the collecting plates and dislodge the particles. Rappers are classified into two categories:

- Impulse types which produce an impact or hammer blow. A magnetic system provides controlled blows (essentially continuous rapping) which eliminates rapping puffs characteristic of intermittent rapping systems. Impulse rappers are most useful for cleaning collecting plates.

- Vibrator types which produce a continuous vibration for some duration. These are usually operated intermittently. They are usually used for corona-electrode cleaning.

The particles fall into the collection hoppers and are removed for disposal. Cleaning of the ESP collecting plates is critical because collected particles may be lost by re-entrainment into the gas stream while still inside the precipitator.

Newly designed ESPs have larger wire-to-plate spacings and use rigid rod discharge electrodes instead of wire. The newer ESPs are capable of operating at higher voltage, which increases the electric field strength and the subsequent particle capture. Many ESPs are equipped with advanced controlled power supplies which monitor electrical condition and maximize performance while minimizing power consumption. Advanced control units provide features such as intermittent energization and spark rate control. Intermittent energization switches off power repeatedly for extremely short durations and maintains ESP performance while minimizing power consumption. Spark rate is important in the electrical operation. Sparking is a phenomenon which occurs because an ionized discharge to the collecting surface resembles an electrical arc. Excessive sparking will reduce the applied voltage and waste power; insufficient sparking may indicate that the ESP is not operating near its full potential. With automatic controls, a desired spark rate can be specified and will automatically be monitored and maintained.

3.3.2 Performance

Operating efficiency of the ESP increases with increasing plate area, increasing voltage and decreasing gas flow rate. Capture efficiency is dependent on:

- Specific collection area (SCA).
- Operating voltage.
- Particle characteristics.

The ESP's size is measured in terms of specific collection area (SCA), which is the ratio of collection surface area to gas volume flow rate. Older ESP designs have specific collection areas (SCAs) which are typically under 300 ft^2/kacfm with a plate-to-plate spacing of about 9 inches. The newer designs incorporate wider plate-to-plate spacings with rigid rod discharge electrodes replacing weighted wire type electrodes. The newer ESPs have state-of-the-art microprocessor power controls, and the geometry permits higher voltage potentials. The particle collection is also subsequently improved.

Electrostatic precipitators are least efficient at capturing particles in the 0.1 to 1 µm diameter size range; however, when designed and operated properly, the ESP is still capable of excellent collection of particles in this size range. Typical electrostatic precipitators capture submicron particulate with approximately 90 to 99% efficiency. The efficiency increases to over 99.9% for particles of 5 µm and larger. Operation is very sensitive to fluctuations in gas flow, particulate loading, and factors which affect particle resistivity, including temperature and particulate and gas composition.

The ESP is very efficient at capturing particles of all sizes, however, it is not efficient at capturing particles that have either high or low resistivities. Resistivity is a measure of the resistance of the particulate matter to being charged and is a function of particle composition and gas temperature. Particles with high resistivity (greater than 2×10^{11} ohm-cm) are difficult to charge and collect. Also, once collected, they do not readily give up charge to the collector plate and tend to build up on the electrode. The ion current generated by the electrodes must pass through the particle layer before reaching the grounded plate. The current gives rise to an electric field in the layer, and when the dust layer builds, this field can become large enough to cause sparking, known as "back corona." When sparking occurs the electrical power input to the ESP must be reduced. The reduction limits the collection efficiency of the process. Low resistivity particles (less than $2x10^8$ ohm-cm) can also be a problem. At this resistivity, particles are easily charged and collected, but the low resistivity will cause the collected particles to give up their charge to the collector plate and easily become re-entrained in the flue gas. Particles with resistivities between $2x10^8$ and $2x10^{11}$ ohm-cm are most efficiently collected. Parameters which influence particle resistivity include mineral composition, density, and flue gas temperatures, moisture, and sulfur content. Resistivity increases with increasing temperature and decreasing moisture and sulfur content. Effective acid gas removal upstream of the ESP results in an increase in resistivity and a corresponding decrease in ESP efficiency. Resistivity can be reduced by adding a conditioning agent such as sulfur trioxide, ammonia, or water vapor to the flow.

Other factors which may adversely affect ESP performance include:

- Flyby of the particle due to exceptionally high operating gas flow rates in which the particle travels past the collection plates with enough speed so as not to be affected by the charged field (i.e., the particle migration velocity imparted by the ESP is insufficient to move the particle to the collection plate in the time available before the particle moves past the length of the collection plate).

- Misalignment of the electrodes and collector plates.

- Dust buildup on the electrodes or collection plates.

- Erosion or corrosion of the collection plates.

- Leakage of scrubber liquid when pH is too high (wet ESPs only).

- Re-entrainment occurring from re-dispersion of collected particles during rapping of the electrodes, seepage of collected dust from the hoppers, and direct scouring of collecting electrode surfaces by the gas stream.

- Undersized equipment.

- Presence of “back corona”, as discussed above, which is due to particle buildup on the collection plates.

Within the last 2 to 3 years, manufacturers have developed advanced PC-based ESP controllers which regulate ESP control to improve power delivery. The advanced controllers are limited to the same peak power, however, the controllers are capable of managing power delivery and avoiding slow power ramping, such that over time a higher average power throughput is achieved. In addition, these “smart” ESP controllers can incorporate a PM setpoint and use data from an opacity type meter to provide feedback to control PM emissions directly. In addition, these controllers can be readily modem-linked to allow remote ESP performance monitoring, potentially reducing maintenance costs.

3.3.3 Upgrade Options

ESP retrofit upgrade enhancement options include:

- Rapping -- Improve rapping cycle frequency and procedures to minimize PM re-entrainment during rapping.

- Electrical power control system -- As discussed above, the addition of an advanced controlled power system which monitors the electrical field condition can significantly improve ESP performance. Systems may include “intermittent energization”, “pulse energization”, and spark rate control systems. Intermittent energization acts to rapidly turn off and on the electric power to the ESP for short durations. This cycling limits the available time for detrimental back corona to form. Spark rate control optimizes the operating voltage to as high as possible for more efficient particle capture. Pulse energization consists of superimposing narrow high voltage pulses onto a base DC voltage as a way of overcoming high resistivity particle problems.

- Geometry -- Modification of internal plate and electrode geometry to increase plate to electrode spacing, allowing for high voltage potentials and increased PM capture.

- Flue gas conditioning -- Addition of water into the flue gas will act to lower the gas volume flowrate and gas temperature, reducing particle resistivity and increasing particle collection. Also, reagents such as sulfur trioxide or ammonia may be injected into the flue gas to condition particles for lower resistivity.

- Gas distribution -- Improve flue gas distribution so as to provide a uniform velocity distribution to all sections of the ESP. This acts to minimize particle re-entrainment and gas sneakage (gas that does not move through the charging electric field), and reduces local occurrences of high flue gas velocities where PM capture may be low due to low particle residence time. This may be accomplished with the use of flow straighteners such as screens and turning vanes.

- Specific collection area -- An increase in the size of the ESP, usually done by making the existing unit taller, acting to reduce the gas velocity and increase particle residence time, thus increasing the capture efficiency.

The specific retrofit procedures which are most applicable to a given facility must be chosen on a case-by-case basis, depending on the current condition of the existing facility.

3.3.4 Process Monitoring

On-line ESPs can be directly monitored using PM CEMS, as discussed above for FFs.

Additionally, to assure proper operation, the inlet gas temperature, flue gas flow rate, and electrical conditions are monitored.

Temperature has a direct effect on particle resistivity; particle resistivity tends to peak at around 400°F, and decreases at high and low temperature.

The electrical conditions depend on the type of ESP. For the conventional cold-side wire-to-plate ESP, the voltage will range from 25 to 50 kV with even higher voltage for wider wire-to-plate designed electrostatic precipitators. Spark rate is often optimized on site but is generally between 50 and 150 sparks per minute. The higher the secondary current the better (secondary current is the current measured in the corona after passing through the transormer rectifier set). Secondary current may be quenched by excessive particle loading. The secondary current density, which is the secondary current divided by the collecting plate surface area, is often less than 100 nA/cm^2. The secondary current density can be calculated for each field by dividing the field secondary current by the plate surface area in that field. Generally, the first fields have the lowest current density because a significant percentage of the current goes into charging the particles which are captured in fields downstream.

3.3.5 Inspection and Maintenance

Electrostatic precipitators are sophisticated devices requiring automatic controls for rectifier equipment, and measurements systems for rapper intensity, hopper dust level, flue gas flowrate and temperature. Because of this complexity, highly trained maintenance personnel are required. Maintenance is required for cleaning carbon deposits on plates which can cause short circuits, corrosion of plates, and erosion of electrodes. The frequency of inspections and maintenance are typically monthly for external systems (such as power supplies and monitors), and annually for internal systems (such as electrode conditions (electrode alignment; electrode pitting; ash build-ups; ash hardening), electrical connections, hopper performance, electrode insulation, and rapper operations).

3.3.6 Wet Electrostatic Precipitators

Wet electrostatic precipitators, shown in Figure 3-9, utilize water to rinse the collected particle layer off the collecting surface. Wet ESPs must be operated at or below the adiabatic saturation temperature of the irrigating fluid (water) so that the fluid is not evaporated. There are several types of wet ESPs, depending on the irrigation method:

- Self irrigating -- Captured droplets wet the collecting surface.
- Spray irrigation -- Spray nozzles continuously irrigate the collecting surface.
- Intermittently flushed irrigation -- The ESP operates as a dry precipitator with periodic rinsing to replace rapping.
- Film irrigation -- A continuous liquid film flushes the collecting surface.

The wet electrostatic precipitator is used effectively in the following conditions:

- After flue gas has been through a wet scrubber.
- When the flue gas is below the dew point (low gas temperature and high moisture content).
- When the flue gas contains fine liquid aerosol particles.
- When it is desired to handle the dust in a “wet” manner.

3.4 High Energy Scrubbers

High energy scrubbers (“venturi” scrubbers) are very commonly used for particulate and acid gas control on hazardous waste incinerators.

3.4.1 <u>Design Principles</u>

The conventional venturi scrubber consists of a converging section, a throat section (either rectangular or circular), and an expansion section, as shown in Figure 3-10. An alkaline recirculating liquid is usually injected at an angle, in one or more streams, into the throat section or just upstream. The engineering principle, as shown in Figure 3-11, is to accelerate the gas to a high velocity in the throat section, causing atomization of the liquid. In some cases, however, spray nozzles are used to atomize the liquid. The solution droplets are then accelerated to their terminal velocity. These droplets provide a large surface area for collection of particles and are many times larger than the particles in the flue gas. The particles are captured when they collide with the slower moving droplets. As the mixture decelerates in the expanding section, further impaction occurs and causes the droplets to agglomerate. Particle capture is primarily related to the amount of liquid atomization achieved, which is proportional to the pressure drop (gas velocity) across the device.

Once the particles have been trapped by the liquid, a separator (e.g., cyclone, demister, swirl vanes) is used to remove the liquid from the cleaned gas. Mist eliminators consist of a mesh of fine wire or wave plates. They provide a large collection surface area while maintaining a high void space. Their use minimizes the risk of blockage by entrained solid particles and moisture in potential downstream operations.

The most prominent feature of the venturi design is a converging throat section which causes acceleration of the flue gas flow. The scrubbing slurry is introduced at the inlet of the throat and is sheared into fine droplets by the high velocity flue gas stream. A turbulent zone downstream of the throat promotes thorough mixing of the gas and slurry droplets. As the droplets slow down through the diverging section, they collide and agglomerate and are separated from the cleaned gas stream by gravity as the gas passes on to the stack.

Venturi scrubbers use one of two approaches: wetted or non-wetted, as shown in Figures 3-10 and 3-12. When the gas entering the venturi is not at saturated conditions, the wetted approach is used. In this approach, a protective film of liquid is established on the convergent portion of the venturi. This liquid is introduced upstream of the throat and flows down the converging sides into the throat, where it is atomized. The gas is cooled by evaporation and reaches the throat at near saturation conditions. When inlet gases are hot and a significant amount of liquid needs to be evaporated, the wetted approach is preferred. The non-wetted approach is restricted to gases with subsaturation temperatures entering the throat. If the hot gases enter the throat, they will vaporize the water droplets and reduce the device's ability to capture particles.

Scrubbers work best when the flue gas entering the scrubber is fully saturated with water so that none of the injected water droplets tend to evaporate. Evaporation produces a flux of water vapor out from the surface of the target droplets that inhibits the capture of smaller flue gas particles. If the liquid is cooled to a temperature below the gas temperature, the capture of small particles will be enhanced. This occurs due to condensation of water vapor from the flue gas onto the target droplets coupled with the tendency of particles to migrate toward and collect on cool surfaces.

3.4.2 Innovative High-Energy Scrubbers

Flux Force/Condensation/Collision

Flux force/condensation/collisions scrubbers are a variation on the venturi type scrubber. The Calvert Collision Scrubber (CCS), shown in Figure 3-13, is an example of this type of scrubber. Initially, the flue gas is quenched with cooled scrubber water. Gases entering the scrubber are split into two streams which are directed to separate venturi throats where scrubber liquid is injected into the gas steam. The discharged gas/liquid streams from the two venturis are directed toward each other, causing them to collide at a high relative velocity. The head-on collision of the streams causes the droplets to shear into fine droplets, thus improving the efficiency of the device. A mist eliminator is used to remove entrained droplets. Through the use of cooled scrubber liquid, a "flux force condensation" technique is utilized. Flux force condensation is based upon the principle that when a gas stream is saturated with water and then cooled, a portion of the moisture will condense, and the fine particles in the gas stream serve as condensation nuclei. As moisture condenses on the particles, they grow in mass and are more easily collected by conventional impaction. Therefore, the condensation enhances the scrubbing system's collection of fine particles, acid gases and metals.

Free-Jet

Free jet scrubbers have the same basic configuration of venturi type scrubbers (i.e., quench, scrubber, and moisture separator). Figure 3-14 shows several types of free jet scrubbing systems. The energy for moving the gases through the system and cleaning the gases is provided by the injection of a compressible fluid (typically steam or air) from a supersonic ejector nozzle which is located inside the flue gas duct. The amount of fluid added through the ejector is proportional to the mass of gas flowing through the system. The turndown capacity of the system is high because the ejector supplies the energy required to move the gases through the system. At the exit of the ejector nozzle, water is injected into the high velocity flow. The velocity of the steam or air breaks the water into small droplets. The flue gas and ejector fluid mixture then passes through a subsonic nozzle in which additional water spray is injected. Finally, the gas passes into an expansion section where free jet mixing takes place, aiding in further particulate agglomeration and capture. The primary advantage is improved capture efficiency compared with conventional venturi scrubbers and lower total energy requirements. Disadvantages include the potential need for an on-site steam supply for the ejector driven systems.

Rotary Atomizing

In rotary atomizing scrubbers, the flue gas is saturated and passed through a "curtain" of liquid droplets, generated by a rotary atomizer disk. A rotary atomizer spins at speeds above 10,000 rotations per minute, creating the droplet curtain. Advantages include efficient collection of submicron particulate compared to venturi type scrubbers and performance that is relatively independent of the flue gas flow rate. Disadvantages are temperature limitations of rotary mechanical equipment and lack of operating experience.

Rotor Filter

Flue gas passes through two rotors, each made up of five counter-rotating wheels and driven by a separate electrical motor. The wheels project V-shaped airfoil-type spokes that generate vacuum and centrifugal forces when they are in rotation. Particulates are mechanically removed from the flue gas by the centrifugal force of rotation, which will funnel them into the cape, or wall of the Rotor Filter. The leading edge of the spoke causes the particles to conglomerate into larger particles, which facilitates their removal. Additionally, it has been shown to remove gaseous pollutants such as sulfur oxides by conglomeration. Rotor filters have been shown to achieve performance levels of less than 0.01 gr/dscf on medical waste incinerators.

Electrodynamic Venturi

The Electrodynamic Venturi (EDV) concept involves a series of steps consisting of saturation, expansion, condensation, ionization, and filtration. The flue gas is saturated in a water spray tower and passed into an "Agglo-filtering Module" in which the gas is expanded; expansion of a gas saturated with water vapor produces a state of supersaturation. Particles act as condensation nuclei and a film of water is formed on the surface of the particulate. The supersaturated gas then enters an "Electro-filtering Module"; a high voltage electrode is mounted on the axial centerline of the module to charge the wetted dust particles and droplets prior to filtration. In the final stage, the flue gas containing the ionized encapsulated particulate is passed through a curtain of positively charged water droplets. Particulate matter is removed by impaction with the water droplets, which is boosted by the electrostatic attraction effect. EDVs have been shown to achieve performance levels of less than 0.005 gr/dscf on medical and hazardous waste incinerators.

3.4.3 Performance

To obtain a high collection efficiency, the flue gas throat velocity must be maintained at a specified level. Approaches that can be used to adjust for varying flue gas flow conditions include:

- Variable throat geometries with adjustable throat inserts (shown in Figure 3-15).

- Adjustable butterfly valves, dampers, or baffles in the throat region (shown in Figure 3-15).

- Adjustment of the elbow area in the throat section. Most scrubbers have a "flooded elbow" which helps collect entrained droplets before exiting the venturi.

The liquid surface tension and liquid turbidity (amount of solid particles in the liquid) are important to capture efficiency. If the surface tension is too high, small particles will "bounce" off the water droplets. High surface tension also has an adverse effect on droplet formation. High liquid turbidity will cause erosion and abrasion of the venturi section.

High pressure differential venturi scrubbers achieve higher particle removal, however, capture of submicron particles is still relatively inefficient. High pressure differential venturi scrubbers, also known as high energy scrubbers, are often equipped with variable throats for tuning the capture performance and minimizing pressure drop. The high pressure differential is costly in terms of electrical power requirements and is impractical for larger units.

The capture efficiency of venturi-type scrubbers is affected by the following:

- Inadequate scrubber liquid feed due to erosion and corrosion of the scrubber liquid transport system.

- Erosion of the venturi wall dimensions.

- Erratic pressure drops due to changes in the gas flow rate.

- Formation of scale on internal parts.

- High temperatures resulting in evaporation of atomized scrubber liquid droplets.

Advantages to the use of venturi scrubbers include:

- Secondary capture of acid gases.

- Performance is independent of the chemical and physical properties of the particles.

- Can handle high humidity flue gas streams.

- Operate at low temperature thus increasing the change of condensing and capturing volatile metals and organic constituents.

Disadvantages to the use of venturi scrubbers include:

- Steam plume visibility. Flue gas heating may be required to eliminate the steam plume.

- Generation of secondary liquid waste stream. The particulate matter collected in a venturi is wet. This may be advantageous since it minimizes the potential for particulate blow-off during handling and disposal. However, it creates a secondary liquid waste stream with an increased volume compared to dry collection techniques.

3.4.4 Process Monitoring

The essential parameters which should be monitored for optimum venturi scrubber performance include:

- Scrubber blowdown frequency and rate.
- Scrubber water suspended solids.
- Liquid pH.
- Gas inlet temperature.
- Pressure drop across the venturi.
- Gas flow rate.
- Liquid feed rate.
- Liquid-to-gas ratio.

The scrubber operation is monitored by liquid spray rate, gas flow rate, liquid pH, scrubber blowdown rate and inlet gas temperature. The pressure drop is a good indication of system performance (particle capture efficiency). The pressure drop is usually controlled with a variable venturi throat. A pH monitor is used to measure the scrubber liquid pH in order to control the amount of caustic material added to the scrubber sump. A low scrubber liquor pH will cause corrosion, while a high pH will cause scaling.

3.4.5 Inspection and Maintenance

Maintenance concerns include prevention of corrosion and scaling on all scrubber internal surfaces, excessive dust build-up, nozzle damage (abrasion/erosion), plugging and fluid leakage. However, because the venturi is self cleaning, it has high resistance to fouling. Visual inspection is usually required for the throat, nozzles and liquid pump. A more detailed discussion of the inspection and maintenance of all types of wet scrubbers in included in Chapter 3.5.4.

3.5 Low Energy Wet Scrubbers

Wet scrubbers appear in a variety of configurations with widely variable efficiencies for controlling acid gas and particulate emissions.

In wet scrubbing, the flue gas enters the absorber where it is saturated and contacted with the sorbent solution. The sorbent reacts with the acid gases to form salts, which are generally insoluble and may be removed by clarifying, thickening, and vacuum filtering of the scrubber blowdown. Typically, wet scrubbers have a 2-stage arrangement, as shown in Figures 3-16a and

3-16b: the first stage (typically a venturi type scrubber) for HCl and HF removal and a second stage for SO_2 removal (typically a packed or spray tower type). This is done to avoid the build-up of chlorides in the scrubber liquor, which can be highly corrosive. In the first stage, water is used to quench the gas to saturation conditions and HCl and HF are captured in a venturi type set up. In the second stage, a sorbent slurry is used for SO_2 removal in a packed, tray, or spray tower.

Advantages of wet scrubbers include:

- Can provide varying degrees of particulate matter control (high efficiency with ionizing wet scrubbers, low efficiency for spray or packed towers).
- Provide higher levels of acid gas control compared with dry scrubbers
- Generate low amounts of solid waste for treatment and disposal compared with dry scrubbers.

Wet scrubber system disadvantages include:

- Require waste water treatment facilities or drying equipment for scrubber byproducts processing prior to disposal.
- Not as efficient at particulate matter removal compared to ESPs, FFs, or high energy wet scrubbers.
- May require stack gas reheat requirements prior to exhausting to atmosphere.
- Prone to corrosion problems and may require expensive materials of construction.
- Higher operating and maintenance requirements compared with dry scrubbers.
- Accumulate suspended and dissolved solids in scrubber liquors. To keep from being entrained by the gas flow, a portion of the liquid must be replaced with fresh liquor.

3.5.1 Design Principles

Wet scrubbers remove particles from the gas by capturing the particles in liquid droplets and separating the droplets from the gas stream. The liquid injected to capture the pollutants can be water or a solution. This solution is often referred to as scrubbing liquor or scrubbing slurry. The majority of operating scrubbers use lime or limestone as the scrubbing solution because of its wide availability and low cost. Sodium-based scrubbing solutions are also used, but to a lesser extent. This section focuses on lime slurry injection type wet scrubbers which have been proven effective in the removal of acid gases (HCl, HF, SO_2), and to some limited degree particulate matter and volatile metals.

Scrubber Designs

There are a number of scrubber designs currently used on hazardous waste incinerators. These include types such as spray tower, tray tower, packed tower, and ionizing wet scrubbers.

Spray Tower -- A common wet scrubber design is the spray tower, shown in Figure 3-17. Spray scrubbers consist of a vessel with a bank of liquid spray nozzles which are mounted across the vessel cross section. Atomized scrubbing liquid (usually water or a dilute solution of an alkaline agent in water) produced by the nozzles fall through the gas stream, which travels up through the vessel. The scrubbing slurry absorbs flue gas acid gases, forming a disposable sludge. The cleaned gas passes through the mist eliminators to remove entrained liquid and particulate. The liquid droplets must be large enough so that their terminal velocity is larger than the gas velocity, otherwise the droplets will be carried out of the vessel.

Tray Tower -- Another scrubber design is the tray tower (also known as an “impingement-type”) scrubber, shown in Figure 3-18. The flue gas enters at the base and passes upward through holes in one or more perforated plates mounted horizontally across the scrubber. Scrubbing slurry is sprayed onto the top tray from above, and then overflows down onto the subsequent bottom trays. Each of the trays has many small openings; the flue gas is forced up through the openings, forming small jets. The slurry on the tray becomes a “froth” due to the gas passing through it, providing very good contact of the flue gas with the slurry. The jets prevent the passage of the liquid layer through the tray openings. The main disadvantage of tray tower scrubbers is that they cannot handle load variations (flue gas flow variations). At low flue gas flow rates, the slurry will drop through the sieve (weeping), while at too high of a flow rate, the slurry mixture is blown out of the scrubber. Additionally, the tray holes are prone to plugging, and the scrubber must be shut down and cleaned periodically.

Packed Tower -- Packed tower scrubbers, shown in Figure 3-19, incorporate a bed of packing material mounted across the scrubber vessel. Liquid is injected down through the packing material, which is usually a random mixture of individual pieces such as balls, saddles, rings, or shaped solids. The flue gas enters at the base of the tower and flows up through the packing against the slurry flow which is introduced at the top of the scrubber. The packing helps distribute the gas and liquid slurry flows (helps mixing), and provides increased surface area for the gas to contact the slurry, resulting in high removal efficiencies. Operational problems of packed beds are a result of:

- Changes in gas velocity hinders liquid movement through the packed bed.
- Plugging of packed bed with solid deposits.

Ionizing Wet Scrubbers -- Ionizing wet scrubbers (IWS) combine the principles of electrostatic particle charging, inertial impaction, and gas absorption to simultaneously collect particles (including submicron particles), liquid droplets, and acid gases. As shown in Figure 3-20, the IWS consists of two sections: a high voltage ionization section and a packed scrubber section. The gas stream passes through the ionization section where the particles are electrostatically charged. The charged particles then enter the packed bed section where particles are removed by attraction to neutral surfaces (collection plates) and impaction on the packed bed materials. A water or caustic recirculating stream continuously washes the packed bed to remove collected particles and acid gases. Because the IWS is a fractional removal device, particle removal efficiency can be increased by employing multiple units in series. IWS advantages include increased particulate matter as well as acid gas collection efficiency compared to typical venturi type and other wet scrubbers, and low pressure drops.

Reagent Preparation and Injection Equipment

The scrubber slurry side of the process starts with the fresh scrubber slurry being pumped into the scrubber. The portion of the scrubber that contains the slurry solution is often referred to as the reaction tank. Next, the scrubbing slurry is pumped from the bottom of the tank to the slurry nozzles located towards the upper end of the tower. The nozzles spray down against the flue gas flow. The scrubbing solution reacts with the flue gas and most of the droplets fall back into the reaction tank, but some of the slurry (the smaller droplets can become entrained in the flue gas flow and travel up toward the mist eliminators. The mist eliminators serve to trap most of the particles entrained in the flue gas, and they are then washed down to the reaction tank by wash water spray.

Not all of the slurry pumped from the bottom of the reaction tank is sent to the slurry nozzles. A small fraction is removed as waste and is made up for by the fresh slurry feed. The spent slurry is diverted to a thickener or hydroclone which removes moisture. The dewatered slurry is disposed of, and the excess moisture is recycled back into the reaction tank and is also used as mist eliminator wash water.

Limestone and lime-based scrubbing slurries are by far the most commonly used scrubbing reagents. The main advantages of using lime or limestone include:

- The process is simple and has few process steps.
- Capital and operating costs are low and limestone is abundant.
- SO_2 removal efficiency can be as high as 95%; HCl and HF removal efficiency can exceed 99%.

The main disadvantages of lime and limestone based scrubbing systems include:

- Large quantities of waste must be treated and disposed of.
- Limestone systems have a tendency for scaling, plugging, and erosion.
- Large slurry flows are needed, resulting in large pumps with high electrical consumption.

In addition to lime and limestone scrubbing slurries, dual alkali systems are also in use which utilize a mix of sodium carbonate (Na_2CO_3) and lime or limestone. The main advantage of the dual alkali process is that scaling (deposits of calcium solids on the scrubber surfaces) is minimized. Disadvantages to the use of sodium include high cost and that sodium may leak out of the system with the waste and potentially contaminate ground water.

Typically, wet limestone and lime scrubbers employ on-site wet grinding (slaking for lime) for slurry preparation. Figure 3-21 shows a typical limestone reagent preparation system. The raw limestone with a diameter of approximately 1 inch is fed through a weigh belt feeder to a ball mill.

Water is added at the feed chute of the mill. From the mill, the limestone is sent to a classifier which separates the coarse limestone from the fine limestone. The classifier sends the fine limestone to the limestone feed tank to be made into scrubber slurry. The coarse limestone is sent back to the mill for more grinding. Grinds ranging from coarse (70% of the limestone passing through a 200 mesh sieve) to fine (95% passes through a 325 mesh sieve). The finer the grind, the better the acid gas capture efficiency will be, but the energy consumption for fine grinding is high.

The spray nozzles used to control the slurry mixing with the flue gas typically operate between 5 and 20 psi and have corkscrew tips. The nozzles produce many droplets of approximately 2,500 to 4,000 µm in diameter. The acid gas reduction chemistry occurs on the droplet surfaces, so the smaller the droplets, the greater the amount of surface area that is available for reaction, improving acid gas removal efficiency. However, to decrease the droplet size, nozzles with smaller openings are required. The pressure required to push the slurry through smaller nozzles is high, and smaller nozzles tend to plug.

Mist Eliminators

Mist eliminators are used on wet scrubbers to collect slurry droplets entrained in the scrubbed flue gas stream and return them to the scrubbing liquor at the bottom of the scrubber. Mist eliminators are located at the exit to the scrubber. Most of the droplets leave the flue gas flow due to gravity, but the small droplets can be carried out with the gas. If these droplets are not removed from the gas before it exits the scrubber, it can deposit on the ductwork, the induced draft fan, and the walls of the stack. This may lead to pluggage and corrosion.

Most mist eliminators are of the impingement type, where the small liquid droplets impact a collection plate, coalesce, and fall by gravity back into the scrubbing liquor. The mist eliminators are sprayed with wash water to remove accumulated solids. The wash water is generally a mixture of fresh water and clear water from the slurry dewatering system.

Waste Water Treatment

Wet scrubber waste water blowdown treatment can include one or more process operations (depending on waste water composition), including:

- Settling tanks to removed suspected particles.
- Vacuum filters or centrifuges to remove particles.
- Evaporator/condenser.
- Addition of thickener.
- Addition of chemicals to adjust pH.

3.5.2 Performance

Wet scrubber design and operating parameters which influence performance include:

- Slurry pH – Concentration and pH of caustic (such as limestone or sodium) in scrubbing slurry. Efficient contacting of caustic with the acid gases can be achieved by simply increasing the concentration of the caustic in the scrubber solution. A droplet with a higher caustic concentration can absorb more of the acid gas before further adsorption becomes inhibited by mass transfer limitations as the unreacted caustic at the center of the droplet slowly diffuses to the caustic depleted surface of the droplet. As seen in Figure 3-22, generally as the pH of the solution increases (the solution become less acidic), acid gas removal efficiency increases.

- Liquid to gas ratio -- The ratio of the slurry flow rate to the flue gas flow rate is referred to as the liquid to gas ratio (L/G). In general, the higher the liquid to gas ratio, the better the acid gas removal efficiency will be. Typical limestone scrubbers operate at liquid to gas ratios of approximately 30 gallons of slurry for every 1,000 cubic feet of flue gas. Since the flue gas flowrate may vary, the slurry flow rate must also be controlled to maintain the design liquid to gas ratio. Figure 3-23 demonstrates how the liquid to gas ratio (at a constant pH) impacts SO_2 removal efficiency.

- Uniform distribution of the scrubbing slurry – Good acid gas removal efficiencies will not be achieved unless the scrubbing slurry is sprayed evenly into the flue gas. To mix the slurry with the flue gas as rapidly and evenly as possible, it is best to have many small nozzles distributed across the scrubber cross section. If only one or two nozzles are used, pockets of flue gas can escape the scrubber without being treated. Unfortunately, small nozzles have a tendency to plug, so the final design must be a compromise between many small nozzles that evenly distribute the scrubbing slurry but have a tendency to plug and a few large nozzles that do not evenly distribute the slurry but will not plug.

- Uniform distribution of the flue gas -- Care must be taken to ensure that the flue gas flow is evenly distributed across the scrubber. For example, if most of the flue gas goes up the right side of the scrubber and the scrubbing solution is evenly sprayed across the scrubber, there will not be enough scrubbing solution to react with all the acid gas on the right side, causing poor acid gas reduction. The flue gas inlet duct at the bottom of the scrubber is designed to promote even distribution of the flue gas across the scrubber cross section. In some cases, perforated plates are used to help distribute the flow, but these cause the pressure drop across the scrubber to increase and result in a higher electricity consumption by the fan.

3.5.3 Process Monitoring

Wet scrubber operation is monitored by the following key parameters:

- Pressure drop across the scrubber.
- Concentration and pH of scrubbing slurry.
- Liquid-to-gas ratio (ratio of slurry flow rate to gas flow rate).
- Accumulation of solids within the scrubber.
- Induced draft fan power consumption.
- Reagent preparation system operation.
- Inlet and outlet gas temperatures.

3.5.4 Inspection and Maintenance

Scrubber operators must constantly monitor and control the system to ensure proper performance. For example, when load changes occur, the scrubber operator needs to reset the limestone feed rate and use the pH monitor as a controller. In addition to good operation and communication, a preventive maintenance program specified by the manufacturer should be implemented. This should include inspection of scrubber module, mist eliminators, dampers, ducts, fans, slurry equipment, valves, and instrumentation for corrosion, erosion, scale deposits, leaks, and plugging. Visual inspection can allow identification of small problems before damage becomes so extensive that major repair is required.

Mist eliminators tend to be subject to buildup of slurry solids and chemical scale, causing the passages to restrict the flow of the flue gas. The first sign of scale buildup is typically noticed by an increase in pressure drop across the scrubber. Water washing is typically sufficient to prevent serious buildup problems.

Because the scrubber control system is based on flue gas and scrubber flow rates, the operating staff should routinely monitor and record readings from all instruments used to measure these flows. If any of the readings appear abnormal, they should be investigated. To verify liquid flow rates or evaluate pump/nozzle erosion, the operator should monitor pressure in the slurry header and the recirculation pump discharge. An increase in the pressure usually indicates plugging of nozzles. A decrease can indicate wear of the nozzles or pump impellers. Slurry flow in pipes can be checked by touching the pipe. If it is cold at the normal operating temperature, then the line is plugged.

The slurry feed requirement is usually controlled by the pH indicator. The sensor lines where pH measurement elements are used should be frequently backflushed and calibrated with buffer solutions to ensure reliable operation.

3.6 Dry Scrubbing

Dry sorbent injection, shown schematically in Figure 3-24, involves the injection of a dry sorbent fine powder into the flue gas. Acid gas removal occurs as the sorbent reacts with the acids in the flue gas to form solid salts. The solid salts are collected in a downstream particulate collector. The particulate collector can be either an ESP or a FF, however, a FF is typically preferred due to increased capture efficiency and sorbent utilization. This is because the removal process continues in the FF; captured sorbent, fly ash, and condensed volatile matter is held on the fabric and remains exposed to the flue gas, thus allowing for further reaction of unused sorbent with the flue gas in the particulate collector. Dry sorbent injection is usually performed after the flue gas has been cooled, typically with a water quench.

Typically, hydrated lime or sodium carbonate (nacholite or trona ores) sorbents are used. The choice of sorbent depends on the preferred operating temperature. Lime is effective at high temperature whereas sodium must be used at lower temperatures. For lime, SO_2 removal is optimized at 1,750°F while HCl and HF is best at 800°F. In cases where efficient capture is required, this may require the use of multiple injection locations. Typically, large quantities (50 to 300% more than stoichiometrically required for complete reaction with the acid gas) of sorbent are required for efficient control in dry systems. Increased control efficiency and decreased consumption of sorbent can be achieved by increasing flue gas humidity and recycling the reaction products captured in the particulate control device back into the flue gas stream.

In some cases, the sorbent may be injected directly into the furnace section of the combustor, known as “furnace sorbent injection” (FSI). Typically, FSI provides extended sorbent/flue gas contact times compared with injection just upstream of the particulate collector. Due to the high temperatures, limestone is exclusively used; the limestone calcines to produce lime which then reacts with the acids. The primary disadvantage of FSI is that poor sorbent utilization is achieved due to the hindrance of the lime-acid (in particular chlorine) reaction at high temperature and the high temperature sintering of the sorbent particles which closes internal pores and reduces the effective surface area for the lime-acid reaction. In some innovative arrangements, FSI is used in combination with injection upstream of the particulate collector to provide optimum acid gas removal.

Advantages of dry scrubbers compared with wet scrubbers include: no mist eliminator is required, the number of pumps and amount of piping are greatly reduced, and the waste material is in the form of dry particulates, which eliminates the need to treat liquid scrubber wastes and may reduce the waste volume. Disadvantages include low utilization of sorbent, high particulate loadings, and the encouragement of fouling and erosion of the heat transfer surfaces for FSI.

Dry scrubbing process monitoring and inspection and maintenance requirements are similar to those discussed below for semi-dry scrubbing.

3.7 Semi-Dry Scrubbing

3.7.1 Design and Performance

The “spray dryer absorption” (SDA) process, shown in Figure 3-25, is considered a “semi-dry” process since a wet sorbent material is used, but the residue produced is dry. In the SDA process, sorbent is mixed with water to form a slurry solution. The flue gas is dispersed, usually by vanes, through a reactor vessel. There are many reactor designs; cocurrent or countercurrent; up- or down-flow; single or multiple gas entrances. The slurry is injected into the reactor as a finely atomized spray. Acid gases present in the flue gas are absorbed into the small liquid droplets and reacted with the sorbent to form a salt. As the droplets pass through the reactor, heat from the flue gas evaporates the water, cooling the flue gas and forming solid particles of salt. Similar to the dry process, dry solids, including salt, unreacted sorbent, and fly ash, are collected downstream of the reactor in a particulate removal device, which is typically a FF, although ESPs can also be used. In some systems, a portion of the dried product is removed from the bottom of the spray dryer, while in others, it is carried over to and collected in the downstream particulate removal device. As in the dry process, the feed is sometimes recycled to decrease reagent consumption.

The SDA process is capable of higher acid removal efficiencies (typically greater than 95% for HCl and 80% for SO_2) compared with the dry process. The following operations are critical for high removal efficiency:

- The reactor temperature must be maintained high enough to ensure complete sorbent-slurry evaporation and to ensure the production of a free flowing product.

- Lower flue gas temperature favors efficient acid capture. However, the flue gas outlet gas temperature must be maintained well above the saturation level, otherwise corrosion problems will occur.

- Fine atomization of slurry spray and good flue gas/slurry droplet mixing is required.

- The flue gas must be well dispersed throughout the reactor vessel.

- Usage of large amounts of sorbent; typically, in 50 to 100% more that than stoichiometrically required for complete acid gas - sorbent reaction. As with dry sorbent injection, to improve sorbent usage, the collected solids may be either recycled as a dry powder or dissolved and injected through the atomizing nozzle.

- To avoid corrosion or product stickiness, the particulate collector and collection hopper must be either well insulated or heated, and air in-leakage must be controlled to minimize cold spots.

For spray dryers, also known as wet/dry scrubbers, hot flue gas enters the top of the dryer (scrubber) vessel where it is intimately mixed and cooled with a finely atomized lime slurry spray. Figure 3-26 illustrates several spray dryer arrangements. The moisture is completely evaporated, leaving the solids as suspended particulates. Mixing occurs in a turbulent flow field. The quenched and chemically conditioned flue gas then flows to a FF and/or an ESP. The major equipment found in a typical spray dryer scrubbing system includes the spray dryer absorber, the particulate-collection system, reagent and slurry preparation and handling equipment, solids transfer, and process control and instrumentation. In spray dryer systems, the particulate collector is downstream and is considered an integral part of the system.

The spray dryer absorber provides the initial contact between the atomized reactive alkali and the acid-gas contaminants. There are two types of atomizers illustrated in Figure 3-26: rotary disks (or wheels) and dual-fluid pneumatic nozzles. In each case, the slurry is atomized as droplets into the dryer, reacts with the acid gases, and dries to a fine powder which is then carried over into the ESP or FF and removed. The particulate collector also serves as an additional contact point between the dried reactants and acid gases, providing additional removal. Some spray dryer systems operate with partial recycling of the particulates by mixing the captured particulates with the fresh lime in either slurry or dry form before being re-injected into the associated scrubber.

The chosen atomization method affects the design of the spray dryer absorber vessel, including the physical dimensions. For a rotary-atomizer type of spray dryer, which projects the droplets radially outward and perpendicular to the gas flow, the length-to-diameter ratio of the dryer (L/D) is typically 0.8 to 1. The droplets decelerate rapidly owing to the drag forces of the downward-moving flue gas and eventually attain the speed and direction of the flue gas. To avoid wall deposition, the designed radial distance between the atomizer and the dryer wall must be sufficient to allow for adequate drying of the largest droplets. In a dual-fluid pneumatic nozzle type of spray dryer, which atomizes the droplets in the direction of the gas flow (downward), the L/D is typically 2:1. In this design, the sidewall deposition is a minor problem. For either design, optimum spray dryer performance is achieved through proper choice of the L/D, droplet size, and residence time. The designed residence time for most spray dryers is 10 to 12 seconds, however few systems operate at 100% of the design flow rate. Thus, actual residence time for most systems is 12 to 15 seconds. Spray dryers range from 25 to 50 feet in diameter.

Spray dryer temperature is controlled by the addition of water to between 200 to 300°F. The addition of the sorbent slurry increases the total particulate loading (depending on the acid gas level, the loading by up to14 gr/acf) as well as the overall particle size mean diameter (typically to over 20 µm).

3.7.2 Process Monitoring

Spray dryer process monitoring parameters are similar to those for wet scrubber applications:

- Pressure drop across the slurry spray nozzles (to ensure sufficient atomization of slurry).
- Concentration and pH of scrubbing slurry.
- Liquid-to-gas ratio via slurry flow rate and gas flow rate.
- Accumulation of solids within the scrubber.
- Induced draft fan power consumption.
- Reagent preparation system operation.
- Inlet and outlet flue gas temperatures.

Most operational problems associated with spray dryers are due to low temperatures at the exit of the dryer. When the gas approaches the dew point, acid condensation may result in the downstream equipment. Therefore, the flue gas exit temperature is a critical process monitoring parameter.

3.7.3 Inspection and Maintenance

Spray dryer inspection and maintenance is very similar to that required by wet scrubbers. Operators must constantly monitor and control the system to ensure proper performance. For example, when load changes occur, the scrubber operator needs to reset the limestone feed rate and use the pH monitor as a backup. In addition to good operation and communication, a preventive maintenance program specified by the manufacturer should be implemented which is similar to the wet scrubber activities.

Visual inspection of the scrubber section and tanks should be performed on a regular basis to identify leaks, scaling, corrosion and erosion problems. Visual inspection can allow identification of small problems before damage becomes so extensive that major repair is required.

Because the scrubber control system is based on flue gas and scrubber flow rates, the operating staff should routinely monitor and record readings from all instruments used to measure these flows. If any of the readings appear abnormal, they should be investigated. To verify liquid flow rates or evaluate pump/nozzle erosion, the operator should monitor pressure in the slurry header and the recirculation pump discharge. An increase in the pressure usually indicates plugging of nozzles. A decrease can indicate wear of the nozzles or pump impellers. Slurry flow in pipes can be checked by touching the pipe. If it is cold at the normal operating temperature, then the line is plugged.

The slurry feed requirement is usually controlled by the pH indicator. The sensor lines where pH measurement elements are used should be frequently backflushed and calibrated with buffer solutions to ensure reliable operation.

3.8 Flue Gas Cooling

The objectives of flue gas cooling are to:

- Protect low-temperature air pollution control equipment such as fabric filters and cold-side ESPs.
- Saturate the flue gas prior to wet scrubbing.
- Condense vaporized pollutants such as volatile toxic metals.
- Prevent the formation of certain classes of organics due to fly ash catalyzed reactions. For example, by cooling the flue gas rapidly, the formation of PCDD/PCDFs can be reduced.
- Recover waste heat.

Flue gas cooling is required prior to particle and acid gas removal in low temperature devices such as baghouses, cold ESPs, and wet scrubbers. There are four methods for cooling the flue gas leaving the incinerator:

- Air dilution.
- Heat exchanger.
- Water quench.
- Radiation and convection duct cooling.

Radiation and convection cooling utilizes heat transfer from the flue gas flow in a long uninsulated duct. This is the simplest method in principle. However, this method is not considered for further review due to large space requirements, particle sedimentation in the duct, and the lack of the ability for precise temperature control during flue gas temperature and flow fluctuations. The three other methods are discussed below.

3.8.1 Air Dilution

Design Principles

For air dilution cooling, shown in Figure 3-27, cool air is injected directly into the hot flue gas stream. The amount of dilution air required is dependent on the initial temperature of the flue gas and the amount of temperature reduction desired, as shown in Figure 3-28. The resulting mix of the two gas streams produces a stream at an intermediate temperature. Air is usually injected tangentially into the axially flowing flue gas stream. Special air mixing jets may be used so that thorough mixing of the two streams is obtained within a relatively short distance.

Performance

The use of air dilution as a cooling method has certain disadvantages, including:

- Air dilution creates a substantial increase in the total flue gas volume flow rate. This additional flow requires downstream pollution control equipment to be considerably larger.

- The control of both flue gas temperature and velocity is not possible. Downstream devices which are affected by velocity (e.g., pressure drop and efficiency for filters and venturi scrubbers) may be adversely affected by changes in quench air requirements to maintain a target flue gas temperature.

- There is potential for the intake of ambient moisture and dust if the dilution air is not preconditioned. This may cause problems in the downstream equipment and may introduce additional pollutants into the flue gas.

- There is potential for either exceeding the capacity of the blower, causing the exiting flue gas stream to be too hot, or the blower flow rate cannot be turned down sufficiently to provide minimum air flow, causing the flue gas stream to be too cold.

Because of these limitations, air dilution cooling is not generally used as the only means of gas cooling; however, it is often used to make small changes in flue gas temperature, such as pre-cooling of the flue gas upstream of a heat exchanger to protect the heat exchanger tubes from high temperature degradation. Advantages of air dilution cooling include ease of use and implementation and low maintenance requirements.

Process Monitoring

The outlet gas temperature and blower flow rate are monitored by thermocouple and flowmeter, respectively, to assure proper operation.

3.8.2 Heat Exchanger

Heat exchangers can also be used for cooling of the hot flue gas stream. In a heat exchanger, heat is transferred from the flue gas through a common wall to a cooling fluid. Note that boilers are a type of heat exchanger.

Design Principles

Heat exchangers transfer heat through a combination of convective and conductive processes. A wide variety of heat exchangers are commercially available, including gas-to-gas and gas-to-liquid types, as shown schematically in Figure 3-29. In a gas-to-gas heat exchanger, the cooling fluid is typically air (e.g., a recuperator used to preheat combustion air). In a gas-to-liquid heat exchanger, the cooling fluid is a liquid, typically water. The liquid is usually recycled, and liquid cooling is often provided by ambient air blowing and evaporation.

Performance

Liquid heat exchangers are more efficient than gas-to-gas heat exchangers due to their increased capacity to remove heat (due to high heat transfer between a liquid/tube interface compared with a gas/tube interface). However, as mentioned earlier, they have increased in complexity since they typically utilize a closed loop cooling fluid. Liquid heat exchangers also have an increased tendency to promote the condensation of acid gases and subsequent corrosion of common walls.

Advantages to the use of heat exchangers for flue gas cooling include:

- No increase in flue gas volume. Unlike air dilution, and due to the cooling fluid and hot flue gas streams being separated, the mass of the flue gas remains the same and the volume decreases with temperature.

- Recovery (and potential use) of waste heat.

Disadvantages to the use of heat exchangers include:

- The heat exchanger cooling capacity is limited by the heat transfer rate, which is determined by the cooling fluid flow rate, the inlet temperature, and the thickness of particulate matter deposits on the cooling surface. Note that if the flue gas contains significant amounts of particles, particle buildup on the tubes act as an insulator and impair the heat transfer efficiency, known as tube “fouling”. This can be mitigated by the use of high temperature particle removal devices upstream of the heat exchanger or by the use of soot blowers to keep the tubes clean.

- Tube corrosion from condensation of flue gas components (chlorine, sulfur, metals).

- Mechanical failure due to thermal expansion of different exchanger parts at different rates.

- Hot-side tube blockage from soot and flyash deposits.

- Tube erosion in heavily dust laden gas streams.

- Loss of coolant from fire, explosion, power outage, system leak, or mechanical failure of the pump, resulting in a system failure. For heat exchangers using liquid cooling, however, loss of coolant will not cause an immediate rise in temperature due to the remaining thermal inertia of liquid coolant. Additionally, liquid heat exchangers can avoid the immediate effects of a power or pump failure by the use of an elevated supply tank to provide the head necessary to push the fluid through the system.

- Limited ability to respond to an increase in the flue gas flow rate and/or temperature, causing a possible system failure due to high flue gas temperature.

Process Monitoring

The outlet gas temperature and coolant flow rate are easily monitored by thermocouple and flowmeter, respectively. The temperature of the cooling fluid is also monitored to assure proper operation, especially if the system has one pass.

Maintenance

If the hot flue gas contains significant amounts of particles, the heat exchanger tubes will require frequent cleaning. As mentioned above, this problem can be mitigated by the use of a high temperature particle removal device upstream of the heat exchanger or by the use of soot blowers to keep the tubes clean. Other maintenance procedures include service of the pumps and blowers.

3.8.3 Quench

In a water-quench cooler, as shown in Figure 3-30, the hot flue gas is cooled by injection of water into the gas stream. The gas temperature is reduced as the water spray evaporates.

Design Principles

The quench is typically performed in a dedicated cooling vessel. Hot gases enter the vessel and are decelerated so that water droplet evaporation occurs completely within the vessel. To ensure evaporation, the water spray must be atomized into small droplets in sufficient quantities to maintain a constant outlet gas temperature. The amount of injected water must be controlled in response to fluctuations in the flue gas temperature. Because it is difficult for the water nozzles to maintain a small droplet size over a wide range of flow rates, nozzles that are used have either variable flow areas or utilize two-phase flow (high pressure air or steam can atomize water over a wide range of flow rates). Rotary nozzles can also be used to maintain a uniform distribution of water droplets over a wide range of flows.

A water quench is almost always used upstream of a gas scrubber when the inlet flue gas temperature is above the saturation point. In this situation, to ensure that the temperature is lowered to its saturation temperature (which is required by the scrubber for effective scrubbing efficiency), a surplus of water is introduced. Because droplets and particles will tend to migrate to the cooler wall, an inside film of water is often used to wash collected particles from the walls. This water is drained from bottom of the cooling vessel and discarded or recycled. The amount of water typically required to cool the flue gas is shown in Figure 3-31.

When a water quench is used prior to a FF or dry ESP, it is critical that the gas temperature remain above the saturation level and that all the water droplets completely evaporate. Otherwise, corrosion and plugging problems may occur in these devices from condensed moisture and other gases. Complete evaporation is assured by fine atomization and large gas residence times in the cooler vessel.

Performance

When excess moisture in the flue gas is undesirable, the most important consideration is that the injected droplets have a uniformly small size range. Large unevaporated droplets may exit the cooling vessel before they have time to completely evaporate. These droplets may cause problems with downstream equipment and may create a non-uniform temperature distribution in the flue gas. Also, droplets may migrate to the vessel wall, reducing the cooling potential of the device.

Water quench cooling has the following advantages:

- Provides the finest and quickest temperature control of the three cooling methods.

- Potential for capturing acid gases and particles if reagents are injected with the water.

- Low maintenance requirements.

Disadvantages to using water quench cooling include:

- Unless recycled, it has the potential to produce a secondary liquid waste stream when the liquid spray is not fully evaporated.

- It has an increased chance of a visible steam plume.

- It has difficulty in accommodating wide variations in gas flow rate and moisture content.

- Failure modes such as:

  -- Plugged spray nozzles, especially if a dry reagent is used for acid gas control.

  -- Corrosion of spray nozzles. This becomes more of a problem if the spray liquor is collected and recycled and/or if acid gases are present in the flue gas.

  -- Loss of quench water from fire, explosion, power outage, system leak, or mechanical failure of the pump, resulting in system failure. This will cause an immediate rise in temperature.

  -- Increased flue gas flow rate and temperature result in an inability to provide sufficient quench liquid, for quench water systems that are undersized.

Process Monitoring

Quench operation is indicated by monitoring the outlet gas temperature, water flow rate, and nozzle pressure. The outlet gas temperature is monitored with thermocouples. Water flow and nozzle pressure are monitored with pressure and flowrate gauges.

Maintenance

Maintenance requirements include checking (and occasionally replacing) spray nozzles for corrosion and pluggage, and inspecting the water pump system.

3.9 Specialized Metals Control Techniques

New techniques are being developed specifically for the control and capture of individual metals species from combustion sources. Mercury, in particular, due to its toxicity and volatility (making it difficult to capture in conventional air pollution control devices), has received special attention. Techniques for its control include the use of activated carbon, selenium filters, special scrubbers, and sodium sulfide. Additionally, special sorbents have been found effective at controlling metals such as cadmium and lead.

3.9.1 Sorbents

A variety of sorbents have and are being developed that have shown the ability to independently remove trace metals from combustion source flue gases. Sorbents having demonstrated metal capturing potential are shown in Table 3-1, and include zeolites, activated carbon, calcium-based, alumina-based, and silicates. Solid sorbents capture and immobilize the metal by a combination of adsorption and chemical reaction; the metal is reacted and/or absorbed on the surface of the sorbent, which is then more easily removed from the flue gas. The actual mechanism depends on the particular metal and sorbent. Some metals react with the sorbent to form a stable compound; other presumably inert materials, such as silica sand, appear to pick up metals by some type of adsorption mechanism. Note that the adsorption procedure is important since it determines the potential leachability of metal from the captured product. The non-leachable water insoluble fraction is surmised to be that which is chemisorbed or reactively adsorbed, while the leachable water soluble fraction is that which is merely physisorbed.

Activated Carbon Adsorption

Activated carbon has recently seen increased use for the “add-on” control of organics, in particular PCDD/PCDF, and mercury from combustion source flue gases, including municipal waste, medical waste, and hazardous waste incinerators. Various mechanisms have been suggested for the capture on activated carbon; these include physical adsorption in the pores of the carbon, catalytic oxidation to mercury oxides, and/or chemically mediated adsorption based on the presence of oxygen and/or chlorine. The presence of chlorine has been demonstrated to augment mercury capture efficiency.

Design Principles -- Activated carbon has a very large inner pore surface (large surface to volume ratio), which can adsorptively bond a very broad range of substances. Typical activated carbon has a surface area of from 300 to 800 m^2/g; high grade carbon can have surface area of 1,500 m^2/g. Two types of activated carbon are commonly used: formation coke (based on coal) and lignite coke. Lignite coke is more commonly used due to its low cost. In some attempts, impregnation agents have been added to the activated carbon to enhance its control efficiency.

Activated carbon can be used in a couple of different arrangements for the control of mercury and organics in combustion system flue gases. These include:

- Fixed bed process -- In the fixed bed process, flue gas flows through one or more beds of activated carbon arranged in a series; spent activated carbon is withdrawn from the bottom of each bed segment. Carbon monoxide levels are continuously monitored across the bed to minimize the risk of fire. To prevent plugging and contamination, the bed is usually placed after a flue gas particulate control device. Although capture performance tends to increase at lower temperatures, the gas should not be below saturation temperature to avoid condensation of moisture in the bed. Activated carbon tends to lose its adsorption capacity when it gets contaminated with moisture. Typical bed operating temperatures range between 250 to 300°F.

- <u>Fluidized bed process</u> -- In the fluidized bed process, flue gas fluidizes a bed containing activated carbon. The fluidized bed arrangement consumes less coke compared to the fixed bed, however, has a higher pressure drop. Circulating beds have also been used, and have demonstrated very high mercury and dioxin removal. Typical bed operating temperature is similar to fixed bed arrangements, ranging between 250 to 300°F.

- <u>Duct injection</u> -- In the duct injection process, activated carbon is injected into the flue gas upstream of a particulate control device, typically a FF or ESP. Because of the corona discharge phenomena of an ESP and combustible nature of activated carbon, an ESP is not considered the best choice for activated carbon collection from carbon injection systems. Additionally, a FF provides for extended hold-up of the injected activated carbon in the flue gas, allowing for additional mercury removal compared to an ESP; for the same level of control, a higher activated carbon feed rate may be required for ESPs compared to FF. However, relatively no difference between capture using ESP and FF has been demonstrated. In some versions, a cyclone reactor is used to improve the mixing of the flue gas and the activated carbon before it passes to the particulate control device. Activated carbon may also be injected upstream of a rotary atomizer, similar in design to conventional spray drying units. The activated carbon may be injected either by itself as a powder or in a dry or wet solution in combination with an acid gas removing sorbent such as lime, calcium hydroxide, or sodium sulfide. Typically for duct injection, activated carbon is provided at a rate of about 50 to 400 mg/m^3 of flue gas. Duct carbon injection is not recommended for facilities with "wet" pollution control systems (those where the injected carbon would be caught in the wet scrubber) since at this time, the two have not been successfully integrated.

<u>Performance</u> -- The use of activated carbon with either direct duct injection or fixed bed arrangements can control PCDD/PCDF flue gas emissions levels from hazardous waste burning facilities to below 5 ng/dscm of total PCDD/PCDF, and TEQ levels to below 0.1 ng/dscm. Additionally, levels consistently below 0.05 TEQ ng/dscm have been achieved, and as low as 0.005 TEQ ng/dscm in select cases; although, surveyed vendor performance guarantees have typically been limited to 0.05 ng/dscm @ 11% O_2.

In addition to toxic organics control, activated carbon can also effectively control mercury. Fixed bed, fluidized bed, and duct injection arrangements have all been demonstrated to perform at 90+% mercury removal, with some as high as 99% or greater.

Operating parameters that effect activated carbon performance include the following:

- <u>Activated carbon type and specifications</u> -- Carbon type may be defined by general chemical and physical properties. Carbon specifications such as chemical properties (e.g., composition, use of additives or enhancers such as iodine or sulfur impregnation) and physical properties (e.g., particle size, specific surface area, pore size) can significantly affect performance. However, work has shown that activated carbon type has little effect on mercury capture; coal-based, lignite-based, and wood-based activated carbon all performed at similar levels.

- <u>Activated carbon feedrate</u> -- Removal rate increases with increasing activated carbon feedrate.

- <u>Injection location for duct injection process</u> -- No noticeable difference in performance has been observed when activated carbon was injected either downstream of the municipal waste combustor economizer, at spray dryer outlet, or along with the lime used for the spray dryer.

- <u>Temperature</u> -- PCDD/PCDF capture efficiency tends to increase with decreasing flue gas temperature, especially at temperatures below 425°F. Mercury capture efficiency has also been shown to improve at lower temperatures, however, there may be a tradeoff; other research has shown that at higher temperatures, the bond between the mercury and the activated carbon is stronger compared to the bonding occurring at lower temperature.

Flue gas temperature is especially important in carbon bed applications since a temperature spike in the bed may cause adsorbed PCDD/PCDF, mercury, and other heavy metals and organics to desorb and reenter the stack gas emissions stream. However, because most facilities utilize some type of PM control device upstream of the carbon bed, and the inlet temperature to the PM control device must be maintained at a certain level to avoid PCDD/PCDF formation, temperature spikes in the carbon bed should not occur.

<u>Process Monitoring</u> -- Activated carbon processes are often used in conjunction with other air pollution control technologies. Monitoring for these other technologies should be reviewed in the previous sections. The following describes process monitoring to be performed for each of the carbon adsorption applications:

- <u>Fixed bed process</u> -- Fixed bed operations are monitored by flue gas inlet temperature, gas flow rate, carbon monoxide levels, upstream and downstream pollutant concentrations, and pressure drop across the system. Flue gas temperature should be maintained at least 100°F above the dew point temperature for water, and at least 40°F above the dewpoint for acid gases. The bed temperature typically ranges between 250 and 300°F. Carbon monoxide levels are monitored to minimize the risk of fire in the bed.

- <u>Fluidized bed process</u> -- Fluidized bed operations are monitored by bed temperature, bed pressure drop, and flue gas flow rate.

- <u>Duct injection</u> -- Duct injection operations are monitored by flue gas temperature, flue gas flow rate, and activated carbon injection rate.

<u>Inspection and Maintenance</u> -- One maintenance requirement of activated carbon systems is the treatment or disposal of the used carbon. Current treatment ideas include a wash process to remove metals, followed by destruction in the primary combustion source, or vitrifying the activated carbon and fly ash into a glass substance. Destruction in the primary combustion source may be a problem since the carbon may contain elevated levels of mercury and other volatile heavy metals which will be re-released when the carbon is burned. Alternatively, the

used carbon may be directly landfilled, or landfilled after stabilization by techniques such as cementation or polymerization.

Recent studies have shown that post-treatment may not be necessary for captured ash and carbon contaminated with mercury. Captured activated carbon and fly ash were stored for 3 years in different arrangements: open container, plastic bag, solidified by water addition, and stored in open container at elevated temperature (50°C). No significant revolatilization or leaching of the mercury was seen in any of the situations during the three year period. However, the oxygen deficient methane rich environment of a landfill may enhance the desorption of previously captured mercury.

To date, no work has been performed to determine the leachability of PCDD/PCDF adsorbed on the carbon. Thus potentially, the carbon injection technique may only serve to transfer the PCDD/PCDF from the flue gas to a landfill leachate if disposed of directly.

Inspection requirements include close monitoring of carbon monoxide levels, and ash and carbon build-up to prevent fire hazards. Use of combustible substances like activated carbon in an oxidizing environment at elevated temperature requires scrutiny due to the risk of fire and explosion. When present with oxygen, activated carbon has the potential to self-ignite at moderate temperatures. That being said, activated carbon has been used with ESPs operating above 450°F.

High Temperature Earth Based Sorbents

The use of “clay” sorbents (including constituents such as sand, limestone, alumina, silica, kaolinite, bauxite, and dolomite) at temperatures in the range of 500 to 900°C have been demonstrated to capture (or inhibit volatilization of) semi-volatile metals such as lead and cadmium.

3.9.2 Mercury Specific Controls

Selenium Coated Filter

Mercury capture with selenium coated filters was originally developed for metallurgical smelting operations in Europe. Selenium filters consist of a cylindrical shell containing porous material impregnated with selenium. Selenium has a strong affinity for mercury; it combines to form mercury selenide (HgSe), a highly stable compound. The filters are positioned downstream of a primary particulate control device to avoid plugging. Problems with the use of selenium filters include that the gas temperature must be 140°F or less and the gas must be clean of particulate, while keeping the gases from becoming saturated, the use of selenium produces a double threat in terms of disposal of the spent material, and filter blinding and poisoning are potential problems. Spent filters are returned to the manufacturer for recharging, although they have lives of several decades.

Sodium Sulfide Injection

Sodium sulfide injection has been successfully used for mercury control from municipal waste combustors in Europe and Canada and has been tested on one unit in the United States. Sodium sulfide is a crystalline solid that is dissolved into a water solution, and is sprayed into the flue gas upstream of a particulate control device. The solution reacts with mercury to form HgS, a highly stable solid reaction product. Injection is typically performed at a flue gas temperature of 260 to 300°F. It has been shown to have a capture efficiency of from 50 to 90%. Problems with its use include the potential release of hydrogen sulfide fumes from bags of sodium sulfide as they are opened, deposits on nozzles and duct work, proper disposal of resultant secondary waste, proper solution atomization, HgS generated as a fine particulate that is difficult to capture in a particulate control device, and the fact that it can not be used with a spray drying sorbent feed because of potential CaS scaling of the sorbent feed line.

Mercury Scrubbers

Mercury scrubbers have been proposed that rely on the reaction of mercury with chemicals such as sodium hypochlorite or with a chelating agent and cupric chloride, to form water-soluble species of mercury which can then be removed in conventional wet scrubbers. 90-95% mercury removal has been demonstrated. The primary problem is treatment of the contaminated scrubber liquors. Additional research is needed to determine optimum operating conditions and effective chemical additives.

3.10 Catalytic Oxidation

Recent work by Japanese and European researchers has shown that PCDD/PCDF may be controlled by catalytic oxidation using metal (such as vanadium and tungsten oxides on a platinum oxide based substrate) catalysts that are presently commonly used for reducing NO_x emissions through the Selective Catalytic Reduction technique (SCR). The catalytic oxidation of PCDD/PCDF has been shown to occur in a temperature range of about 480 to 660°F. PCDD/PCDF destruction efficiencies of 95 to 98% have been demonstrated, with controlled levels below 0.1 ng/dscm TEQ. For example, operation on a full scale MWC controlled levels of PCDD/PCDF to below 0.1 ng/dscm TEQ, with most levels at or below 0.05. Catalysts are currently available from many vendors including Lentjes, Deutsche Babcock, Siemens, BASF, Huls, Degussa, and SGP-VA. Problems with this method include catalyst fouling and contamination from metals, sulfur, or chlorine compounds, leading to deactivation.

3.11 Sulfur-Based Control

PCDD/PCDF have been found to be either not detected or present at very low levels in coal fired boiler flue gas emissions. This has been surmised to be due to the presence of relatively higher levels of sulfur which may act to suppress PCDD/PCDF formation. This is supported by additional work on the co-firing of coal with municipal solid waste. Full scale testing on a MWC has shown that the addition of coal (containing 19 weight percent sulfur) to the municipal solid waste stream acted to reduce PCDD/PCDF levels from 10 to less than 1 TEQ ng/dscm. Other studies on the co-combustion of coal with plastics and bark have shown very low PCDD/PCDF levels below 0.1 TEQ ng/dscm. With the addition of limestone to the combustion region, flue gas emissions decreased, but PCDD/PCDF emissions increased substantially, further lending evidence to the premise that the presence of sulfur acts to suppress PCDD/PCDF formation.

It has been postulated that the presence of sulfur as SO_2 suppresses Cl_2 formation, thus reducing PCDD/PCDF formation. However, controlled laboratory scale studies have determined that gas phase SO_2 has little apparent effect on PCDD/PCDF formation, and that the presence of sulfur as an upstream reaction product acting to alter the form of the metal catalyst required for low temperature (300 to 400°C) catalytic formation (e.g., $CuSO_4$ instead of CuO) may be the cause of low PCDD/PCDF levels in systems with sulfur.

3.12 Air Pollution Control System Types

The choice of flue gas cleaning components and arrangement depends on characteristics of the flue gas such as:

- Particle size distribution and loading.
- Acid gas content (nitrogen, sulfur, and chlorine).
- Organics content.
- Metals content.

Note that these parameters are influenced by both the incinerator type and waste composition and type. Generally, all air pollution control system can be classified as either dry, wet, or hybrid dry/wet.

Wet

Wet systems are typically selected when the flue gas has significant levels of moisture, “sticky” compounds, and/or when acid gas control is required. In the wet system, a quench cooler is used to saturate the flue gas stream. Venturi and other novel scrubbers may be used for particulate control; additional packed bed, spray or tray type scrubber may be used for additional acid gas and volatilized component capture. The flue gas stream must then be conditioned (heated or dried) before any final polishing (e.g., with HEPA filtration) to avoid moisture condensation in the filters. Advantages of wet systems include rapid and predictable gas cooling, low temperature operation aiding in capture of volatilized metals and acid gases, and ease of byproducts handled in wet form. However, disadvantages include:

- Generation of contaminated secondary liquid stream.
- The requirement for flue gas conditioning (reheating above the dewpoint saturation temperature) if it is desired to use dry filters downsteam of the wet scrubber (without reheating there is rapid degradation of dry filters from wet scrubber moisture carry over).

- Inefficient fine particle collection compared with dry filter systems.

- Increased corrosion potential.

Dry

Dry systems are preferred when the flue gas leaving the combustor does not contain acid gases. Water may be used for cooling; however, care must be taken to avoid cooling th flue gas down to the point where condensation may occur in downstream devices. Dry systems utilize either high temperature particle removal devices such as cyclones (for coarse particle removal) and ceramic or sintered metal filters (for fine particle removal), and/or lower temperature devices such as baghouses and ESPs. Dry systems can use spray driers to control acid gases, although large amounts of secondary wastes (captured dry solids) are generated due to their relative inefficiency.

Advantages of using dry systems include efficient capture of fine particles and avoidance of contaminated liquid waste generation, efficient control of fine particulate, and minimization of corrosion potential. Disadvantages include inefficient or nonexistent capture of acid gases and generation of large amounts of dry scrubbing product.

Hybrid Wet/Dry

The third type of system, a "hybrid dry/wet" combination, uses a combination of both dry and wet components, as shown in Figure 3-32. Dry/wet systems perform dry initial and fine particle removal in a manner similar to that of dry systems; however, the flue gas is passed through a wet scrubber/absorber, which is used to remove acid gases and other volatilized components. Typically, a SDA/FF and wet scrubber are used in series. The SDA is located upstream of the wet scrubber, and is utilized to dispose of the liquid effluent produced from the downstream two-stage wet scrubber. Hybrid systems may be designed to include the advantages of both wet and dry system including generation of dry secondary waste, efficient capture of fine particulate, as well as low temperature capture and control of acid gases and volatile metals. The primary disadvantage is increased capital cost and system complexity. Other potential disadvantages include the re-release of contaminants caught in the wet scrubber liquid when re-injected back into the flue gas stream to cool the flue gas, and the potential for recycling and buildup of trace constituents due to this recycling of scrubber liquor blowdown.

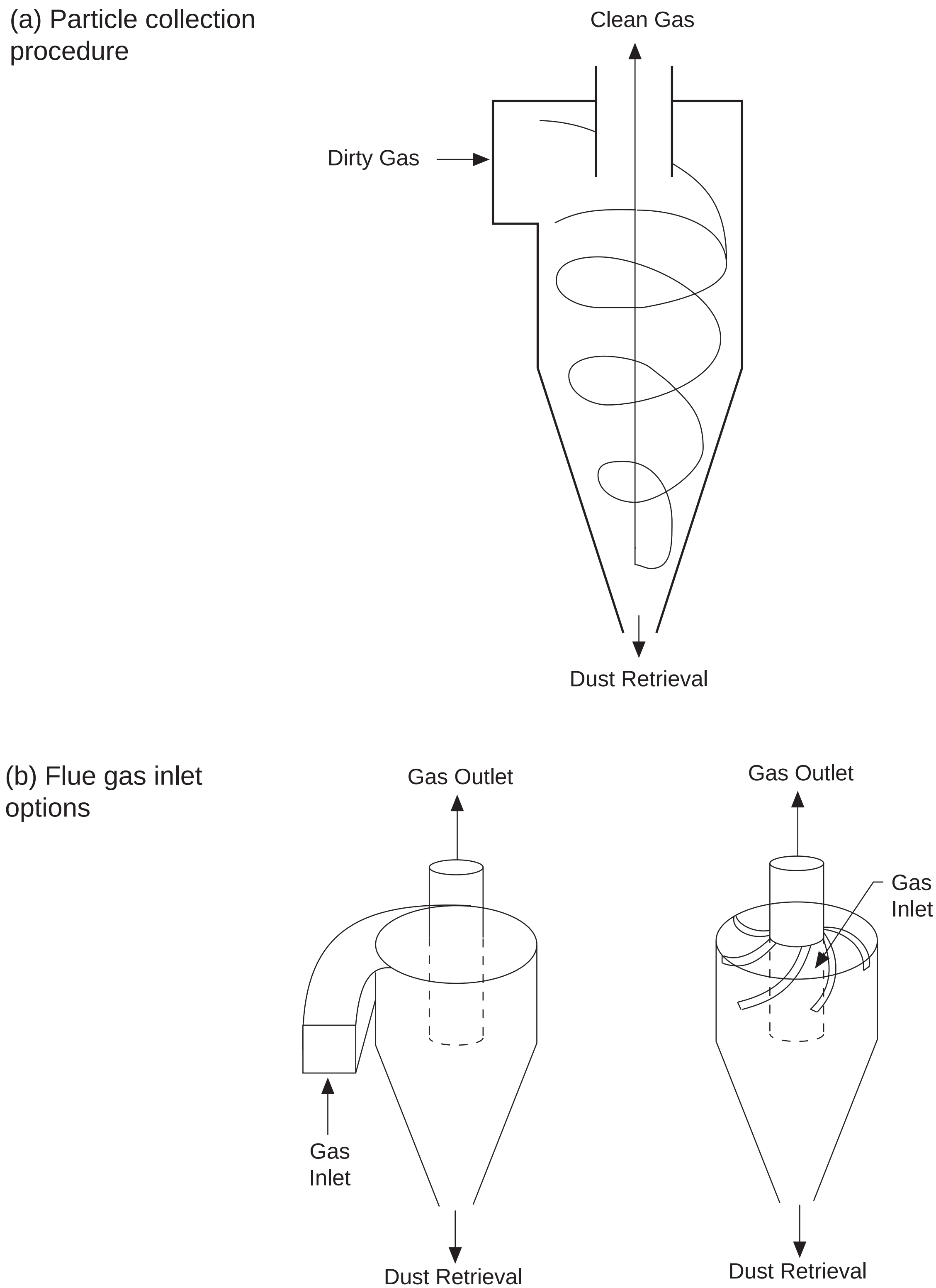


Figure 3-1. Cyclone particle collector.

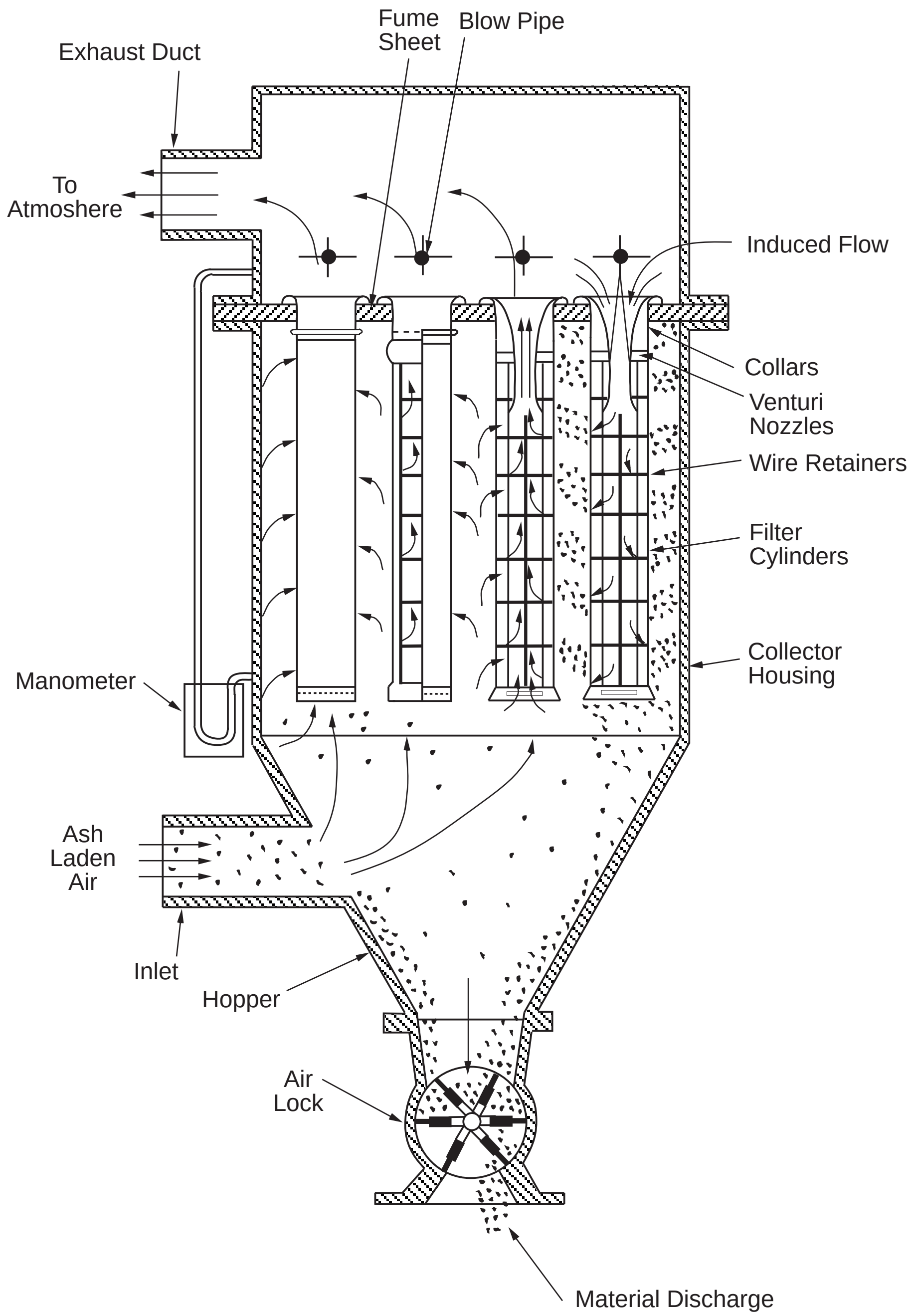


Figure 3-2. Pulse-air-jet type cleaning baghouse.

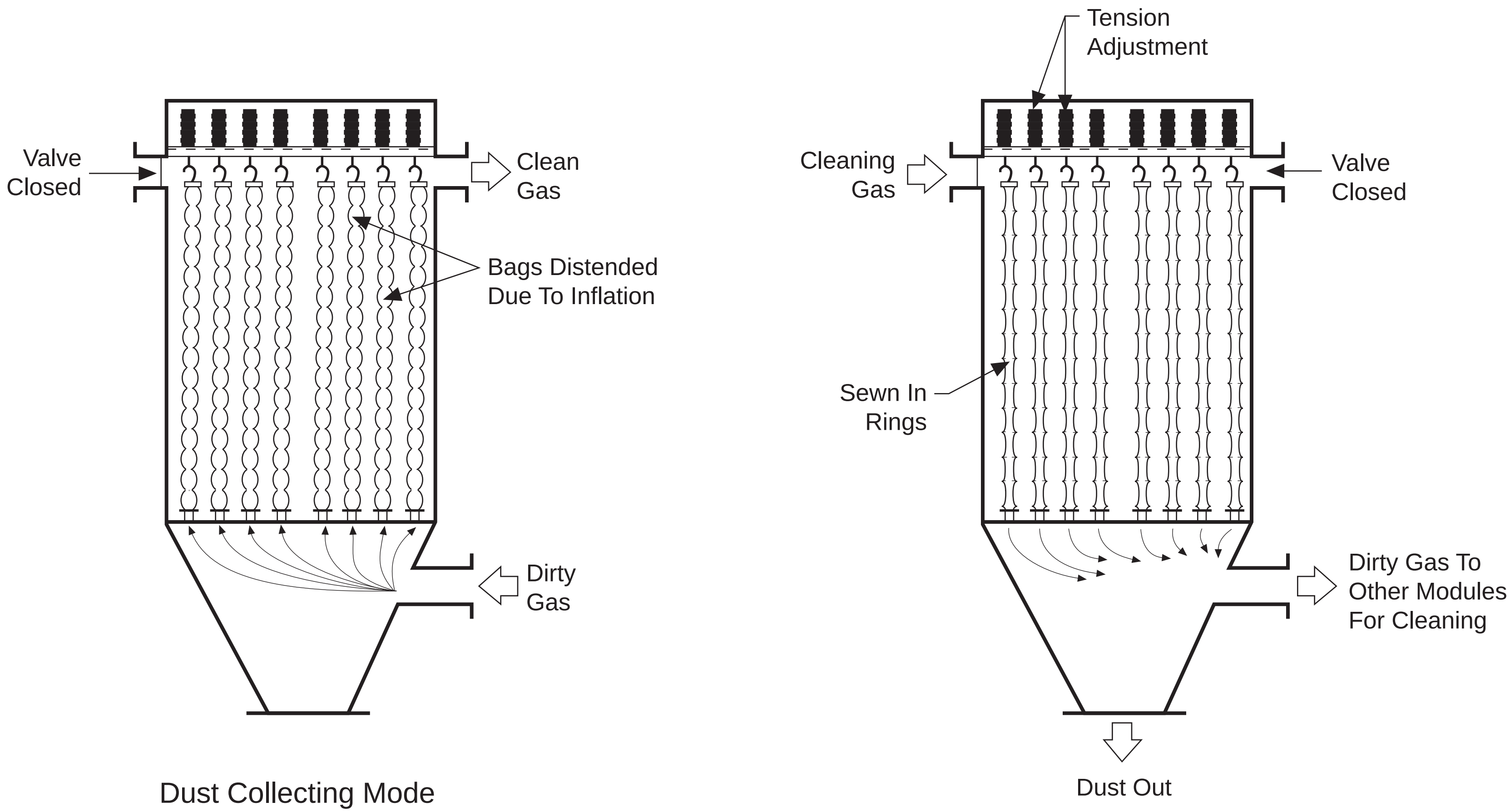


Figure 3-3. Reverse air cleaning baghouse.

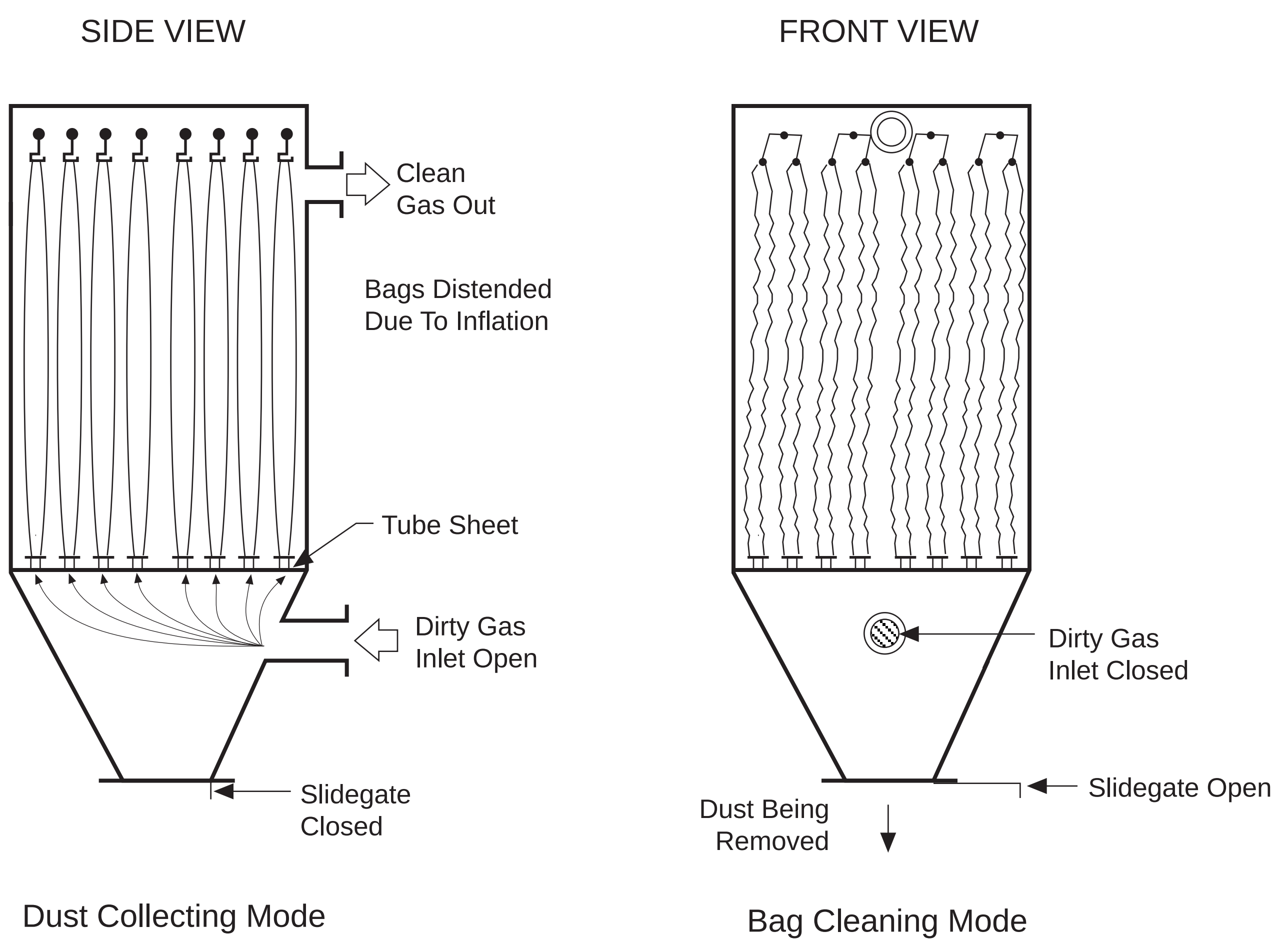


Figure 3-4. Shaker cleaning baghouse.

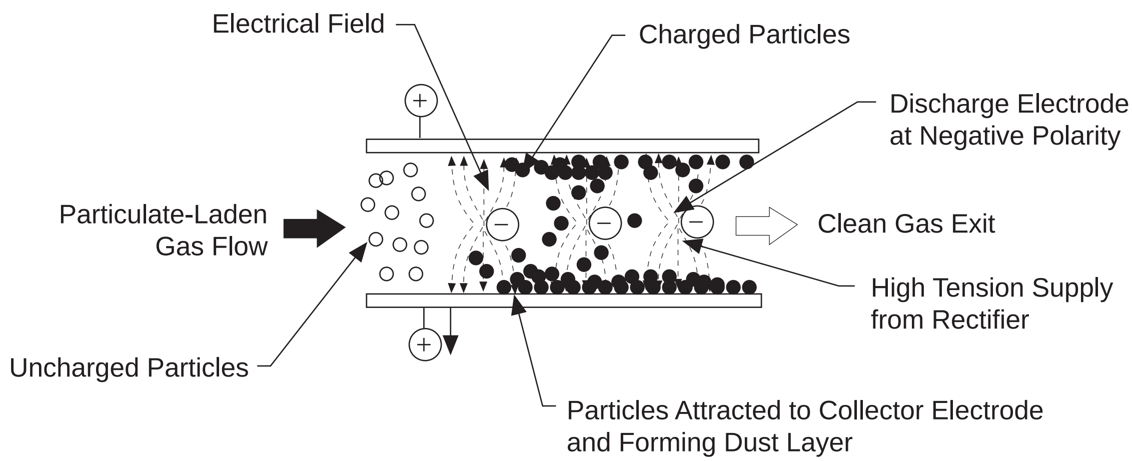
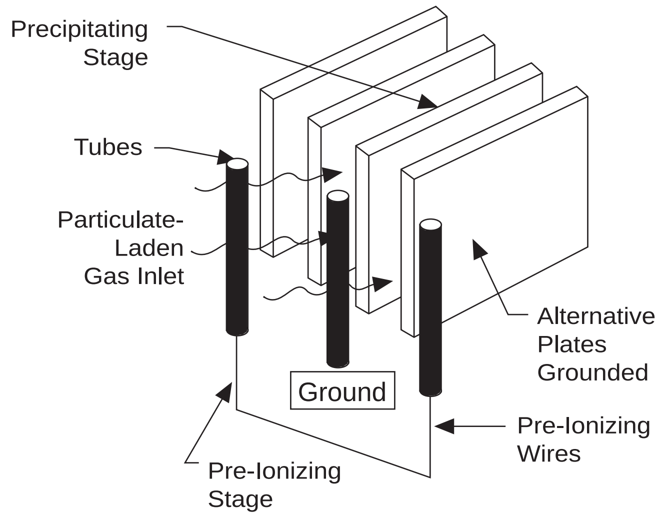
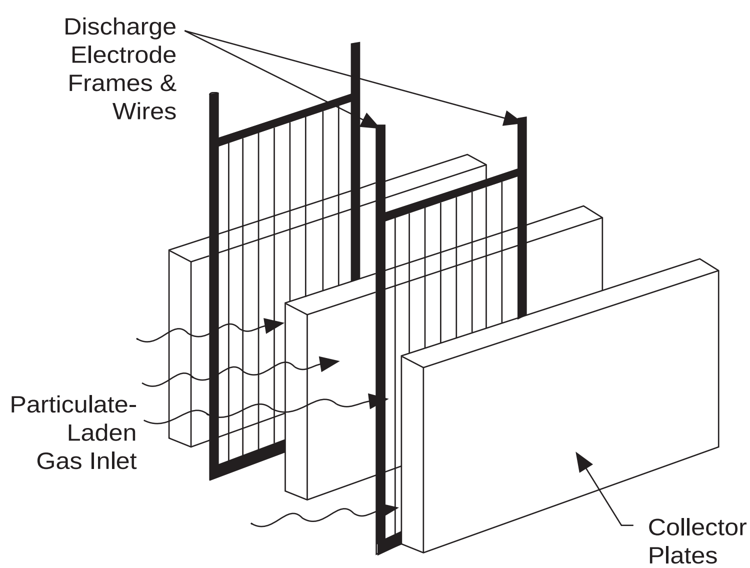


Figure 3-5. ESP particle collection procedure.



(B) Two Stage Precipitator



(A) Single Stage Precipitator

Figure 3-6. One and two-stage wire-to-plate ESP operation.

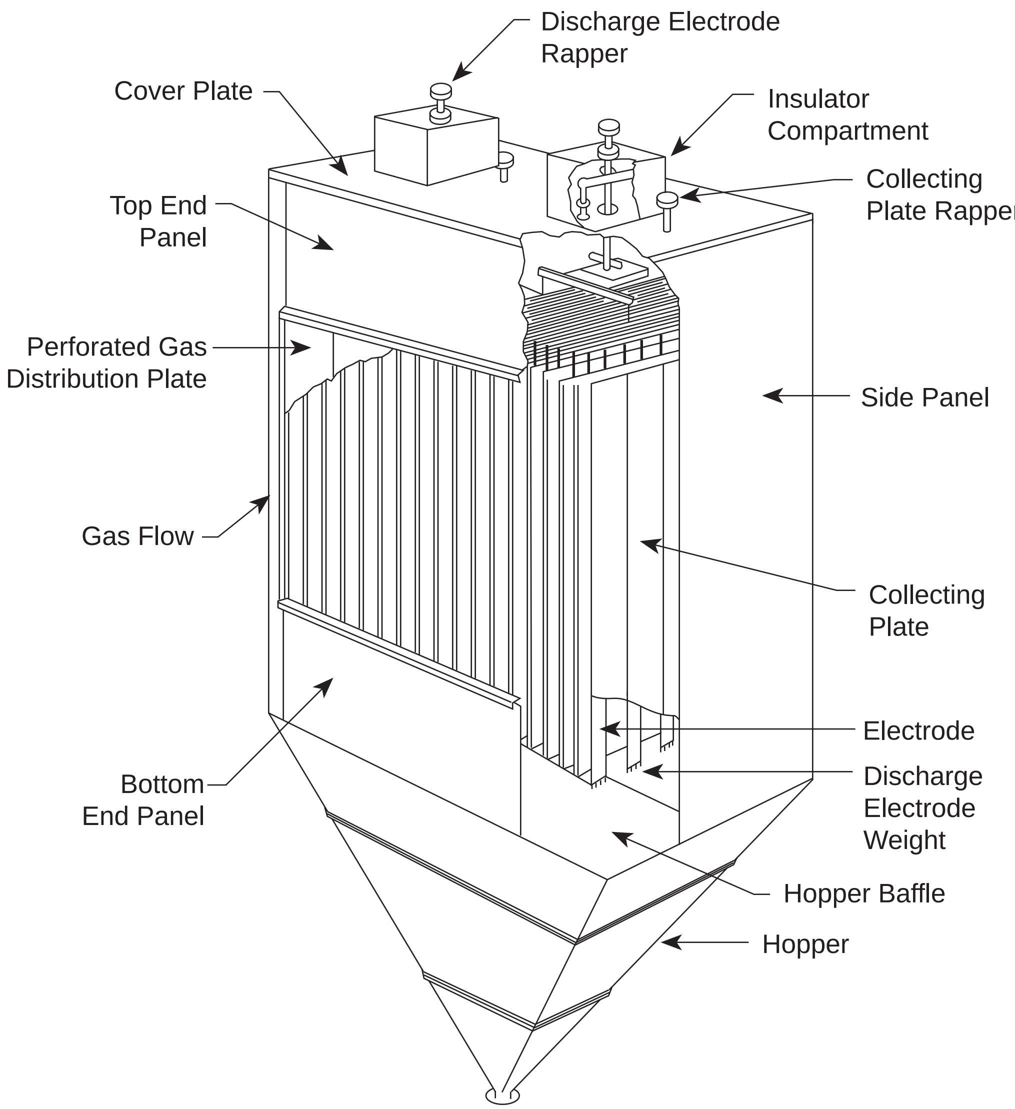


Figure 3-7. Plate type ESP.

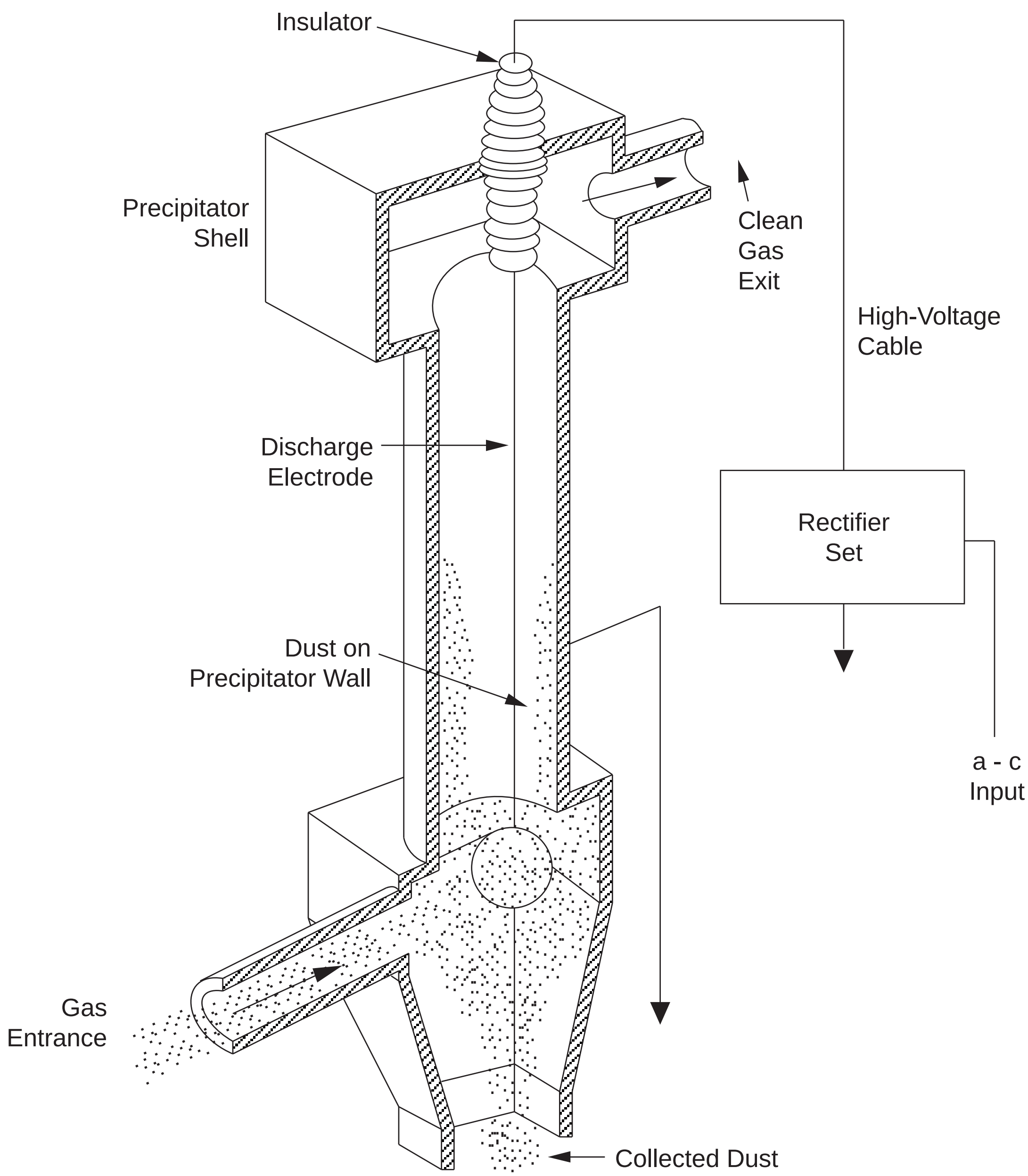


Figure 3-8. Tubular type ESP.

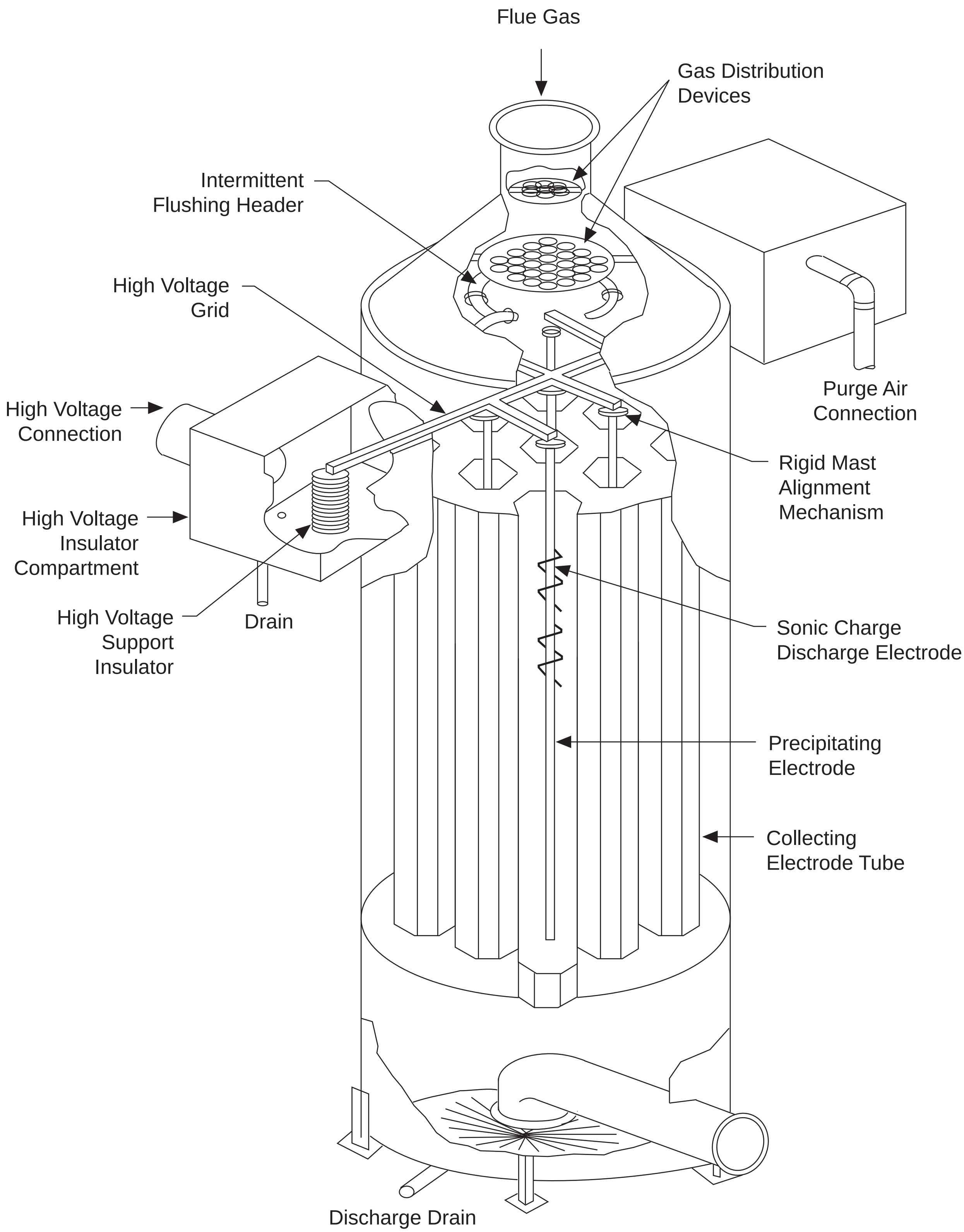


Figure 3-9. Wet ESP.

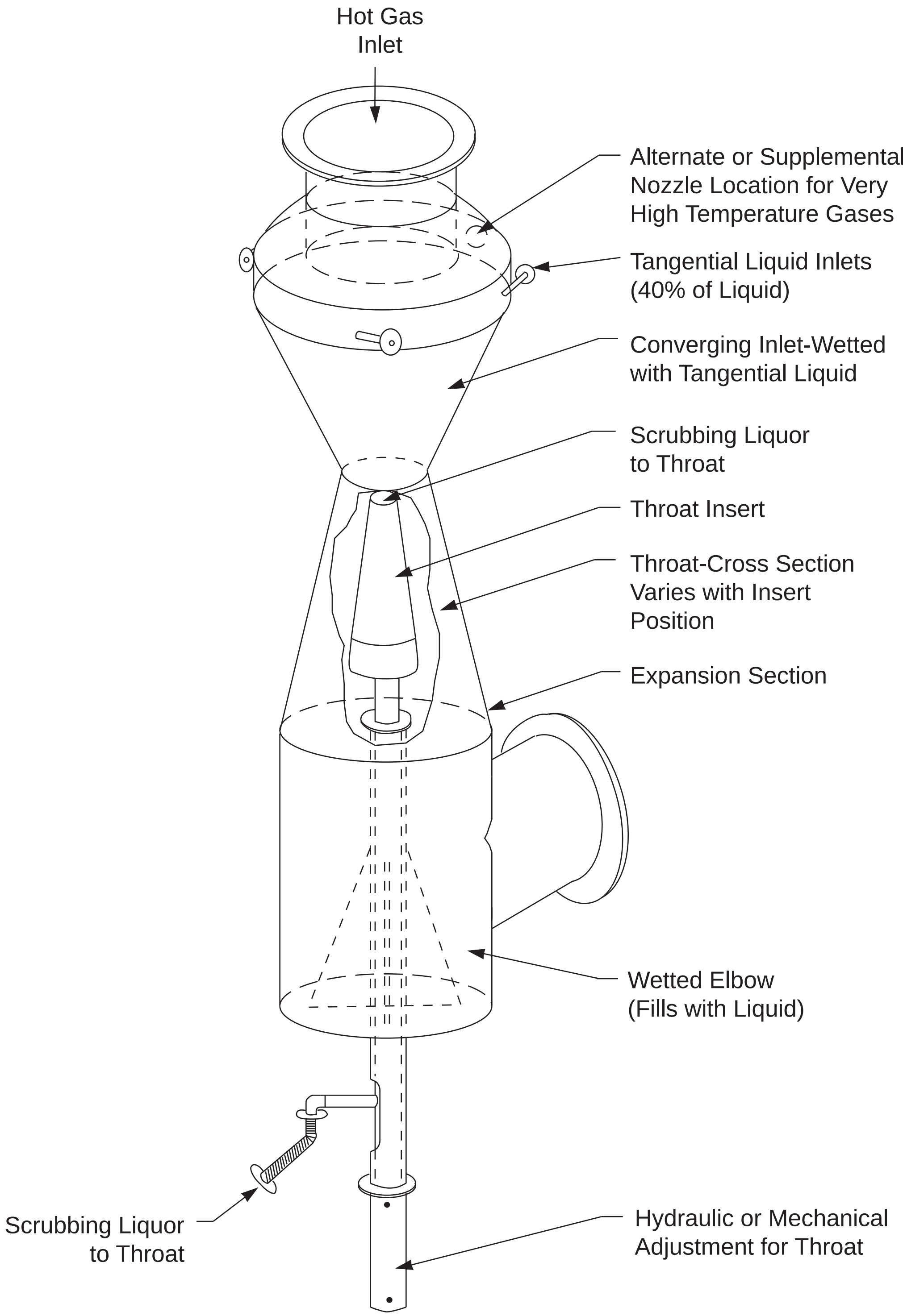


Figure 3-10. Variable throat venturi scrubber with wetted elbow.

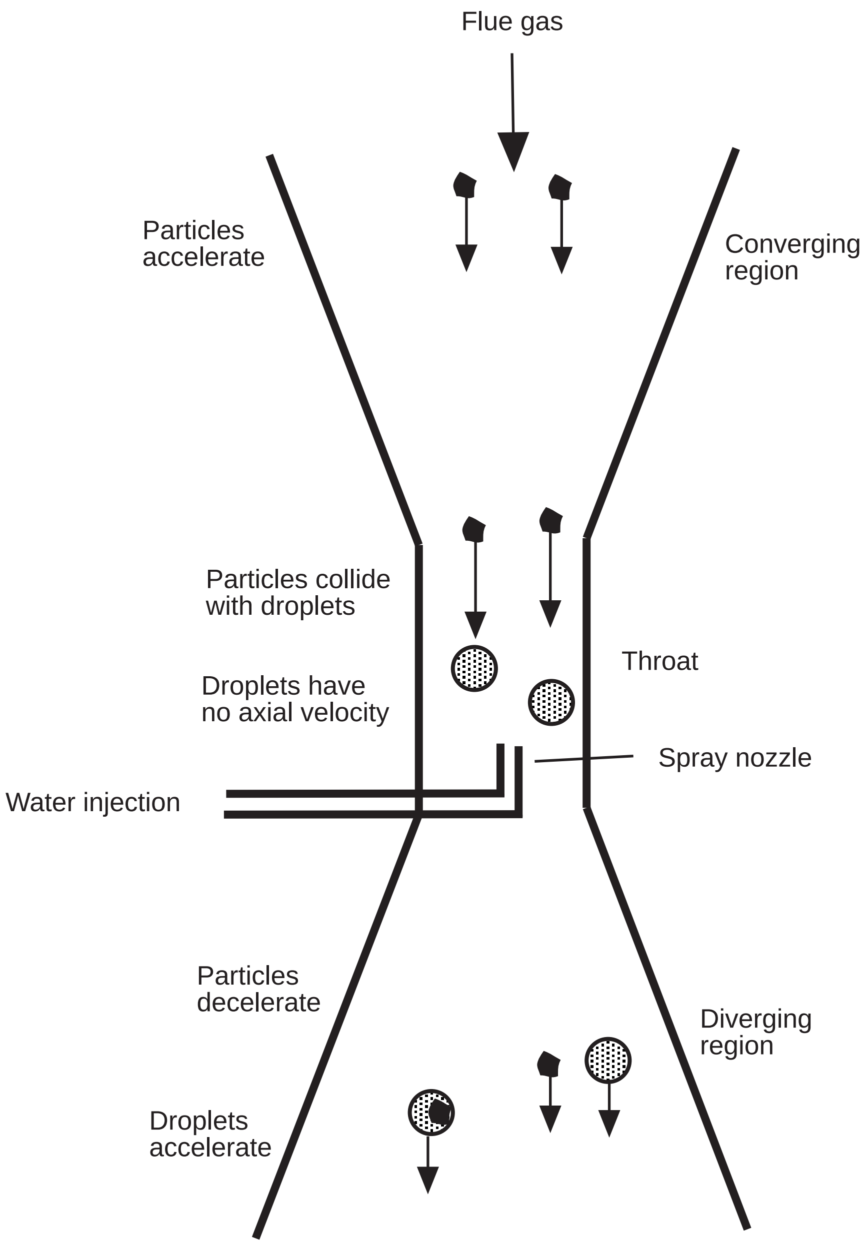


Figure 3-11. Performance principles of a venturi scrubber.

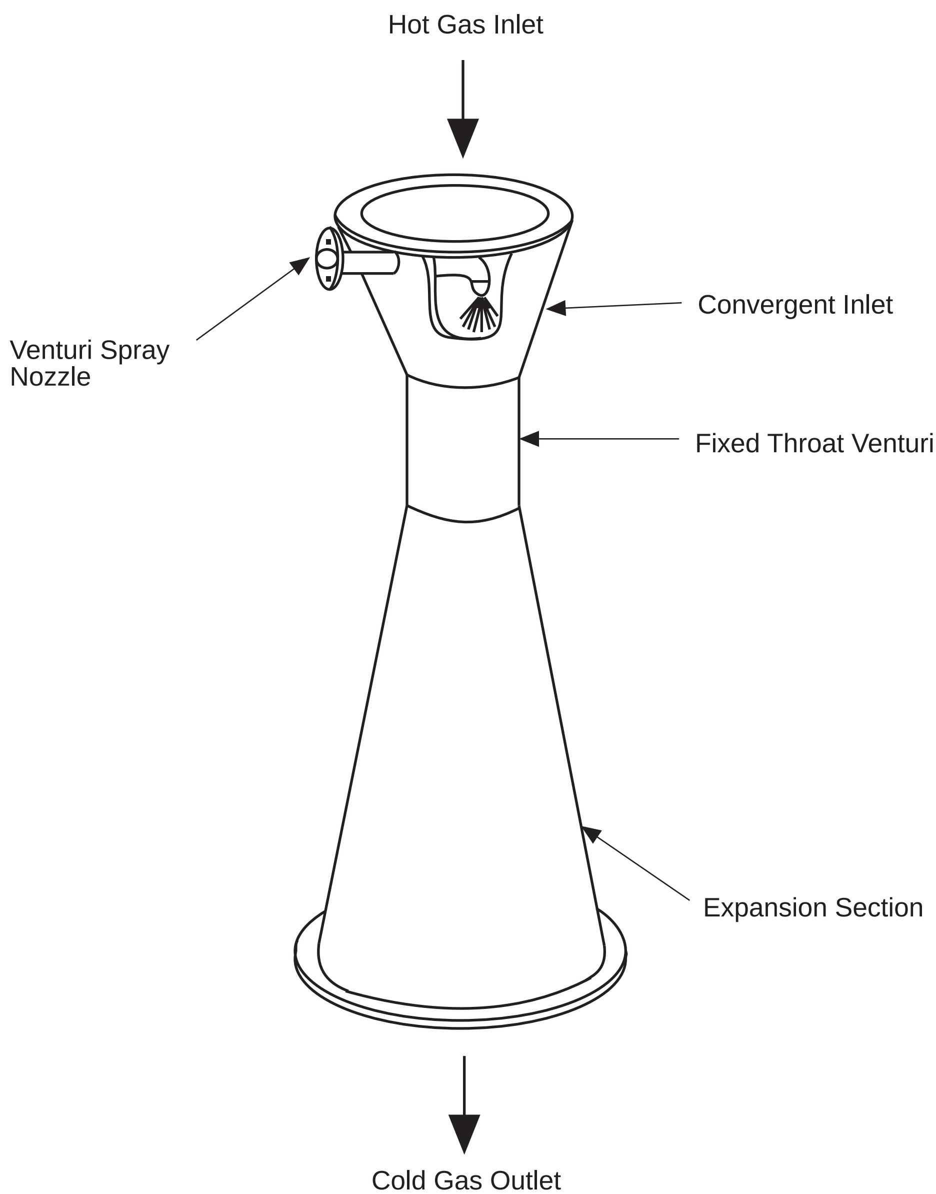
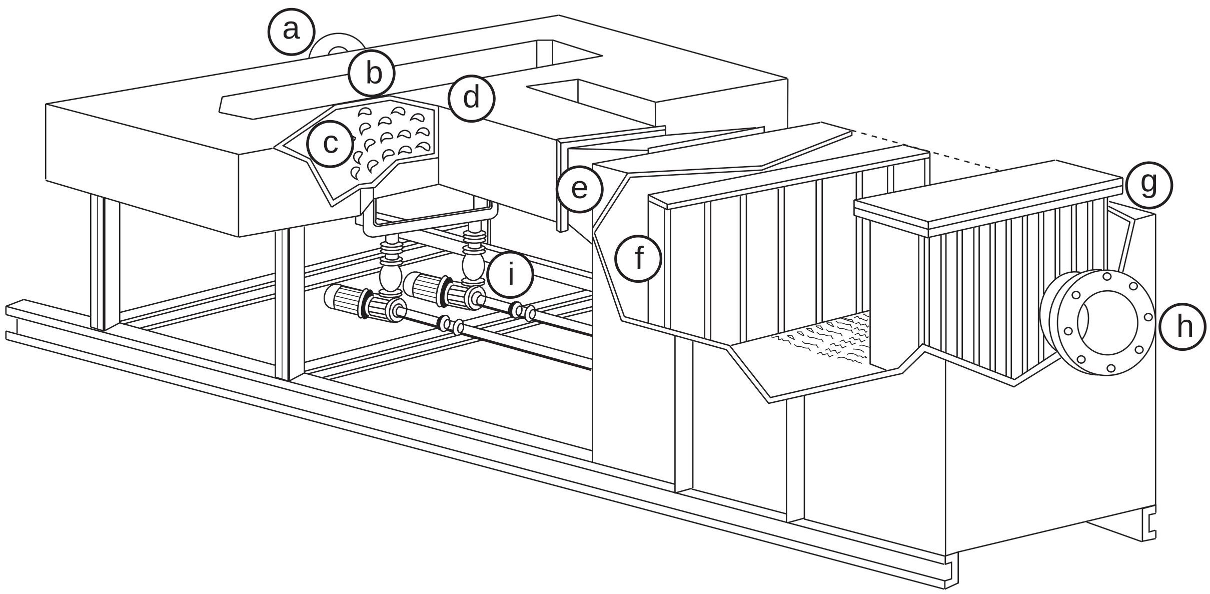


Figure 3-12. Non-wetted, fixed throat venturi scrubber.



a **Gas Inlet**
Flanged inlet for dust, fume and acid gas flow.

b **Throat Inlet**
The gas is split into two equal flows.

c **Throats**
Point of liquid injection (adjustable throats available).

d **Collision Zone**
Submicron particulate and acid gases removed from the gas stream.

e **Energy Recovery Diffuser**
Gas and liquid stream expanded.

f **Primary Droplet Eliminator**
Most of the water removed.

g **High Efficiency Waveforms**
Fine droplet eliminators polish the gas.

h **Gas Outlet**
Flanged connection for clean gas flow exit.

i **Pump**
Returns water to the throat via distribution headers.

Figure 3-13. Force flux/condensation/collision scrubber.

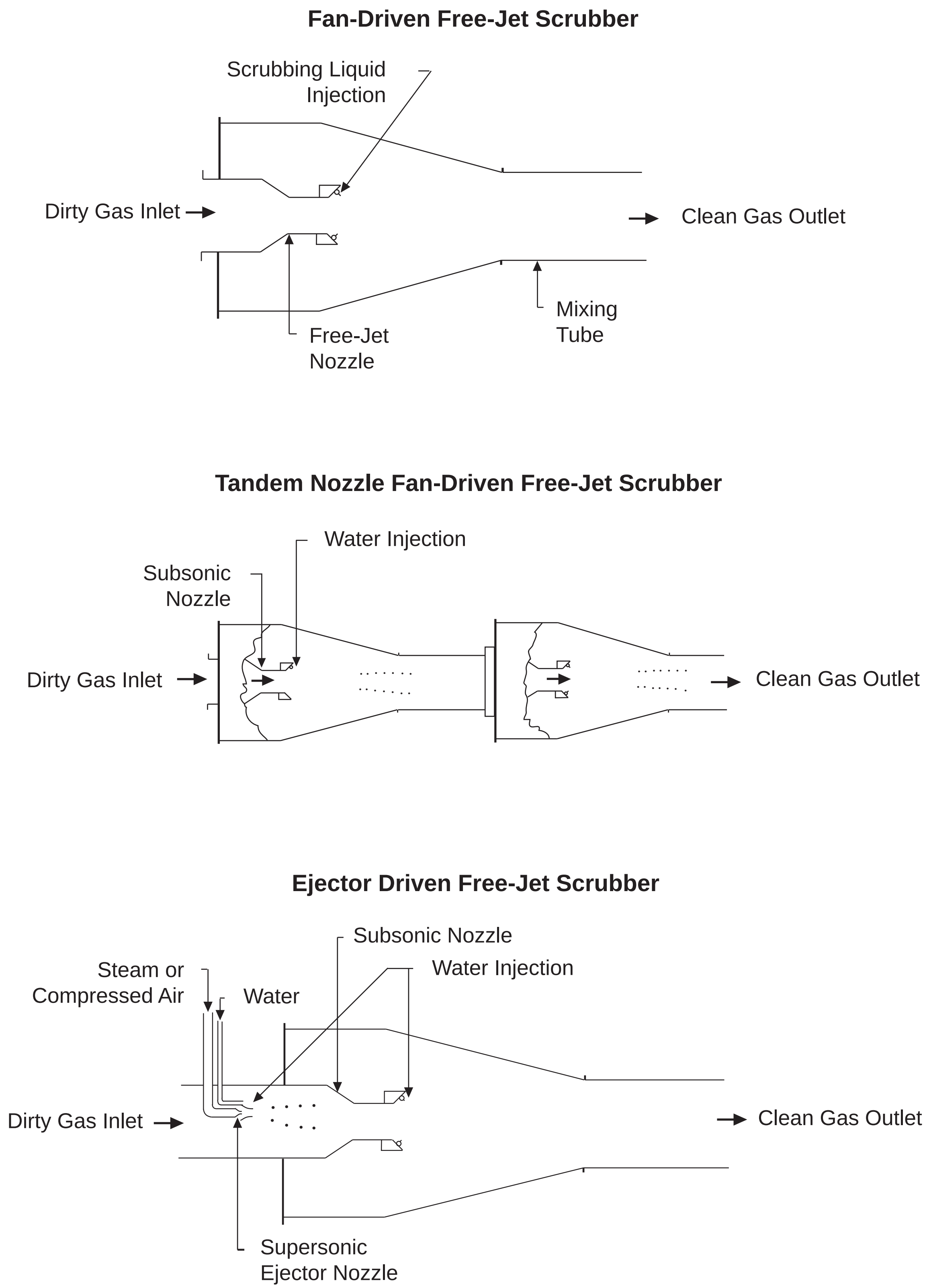


Figure 3-14. Free-jet scrubbers.

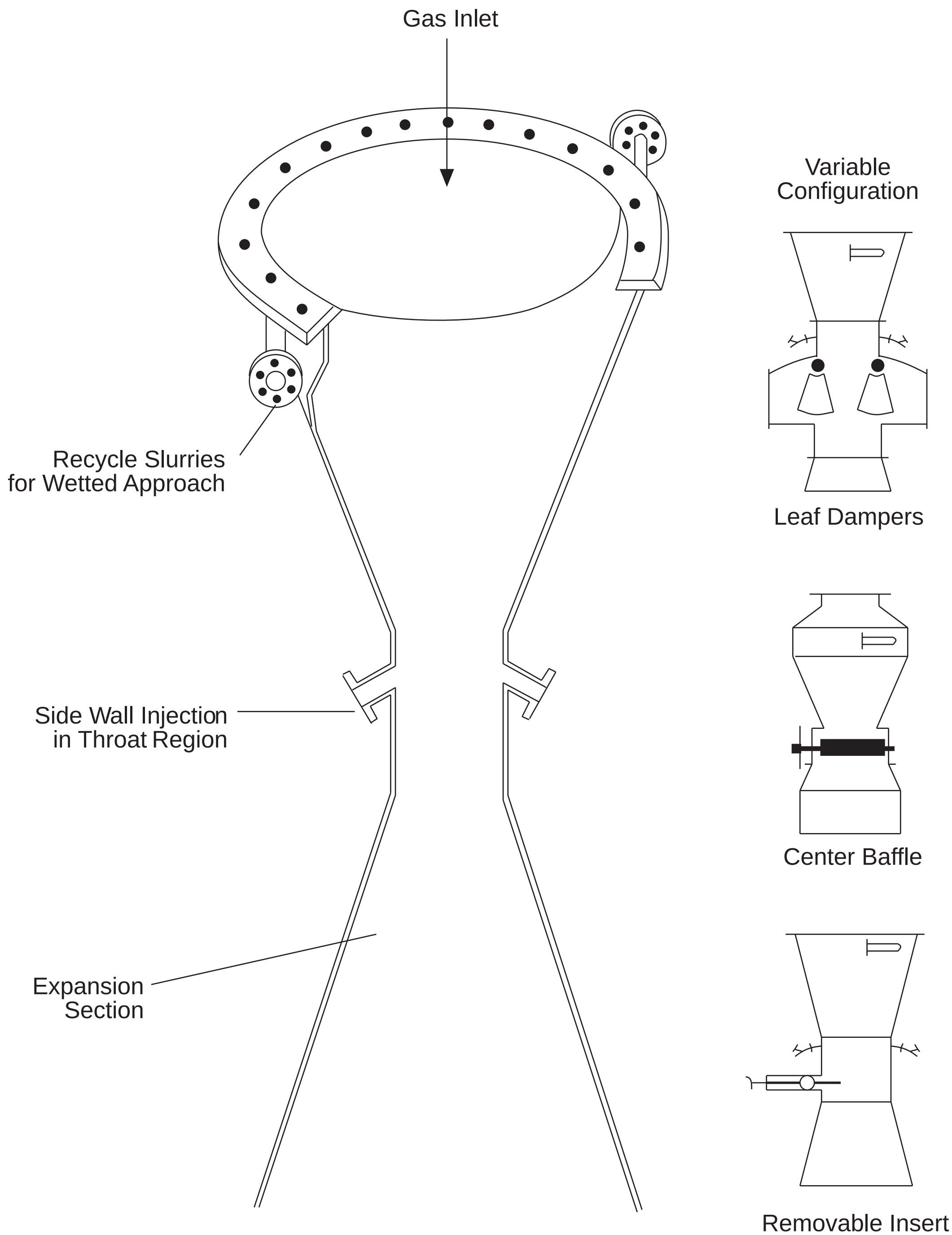


Figure 3-15. Venturi scrubber with different flow control throat mechanisms.

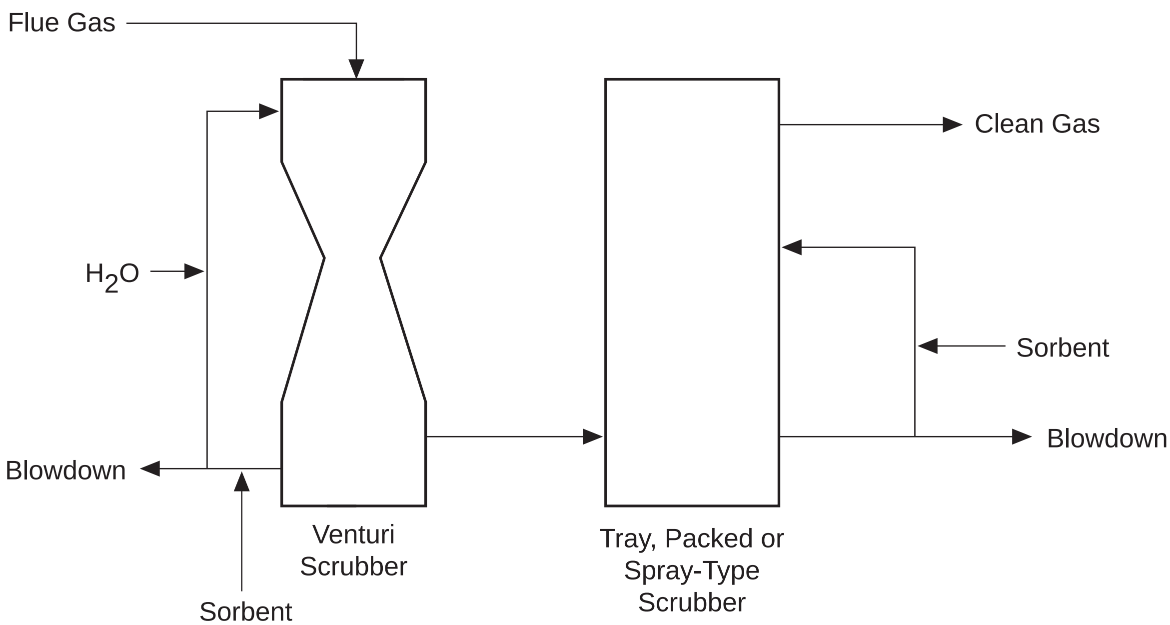


Figure 3-16a. Two-stage wet scrubbing process schematic.

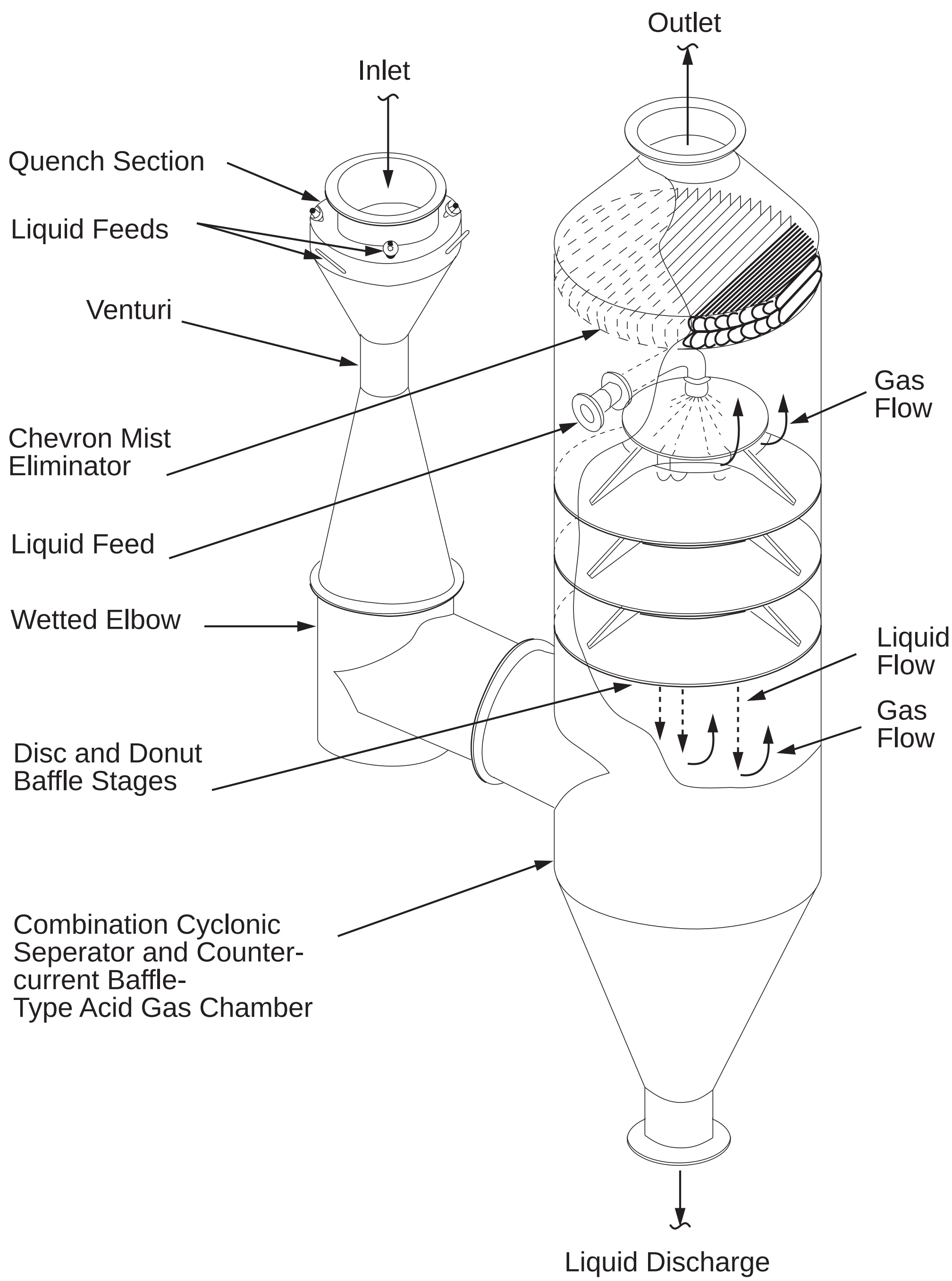


Figure 3-16b. Venturi and tray tower wet scrubbing system arrangement.

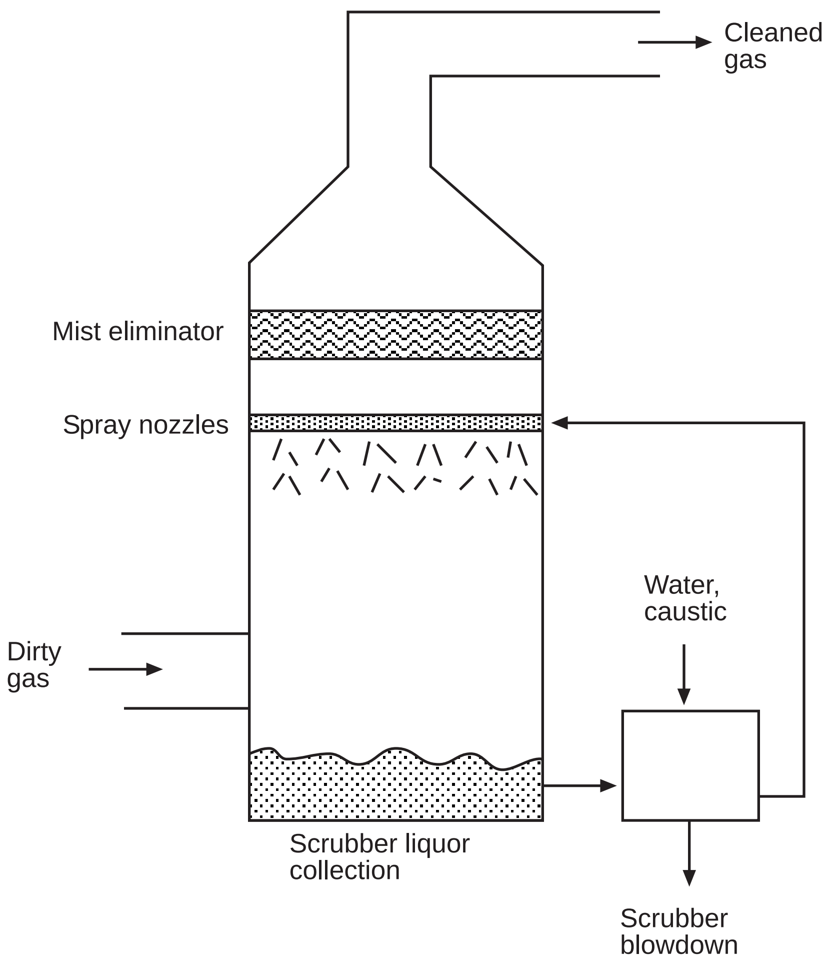


Figure 3-17. Spary tower wet scrubber system.

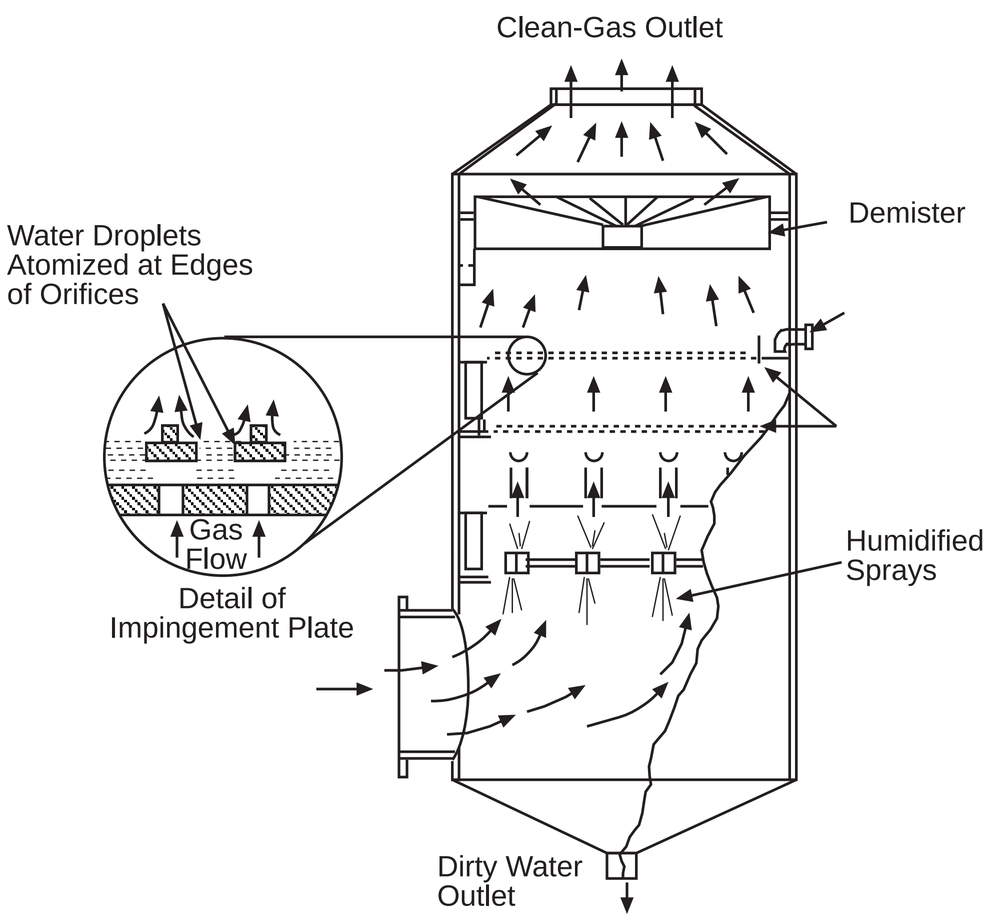


Figure 3-18. Tray tower wet scrubber.

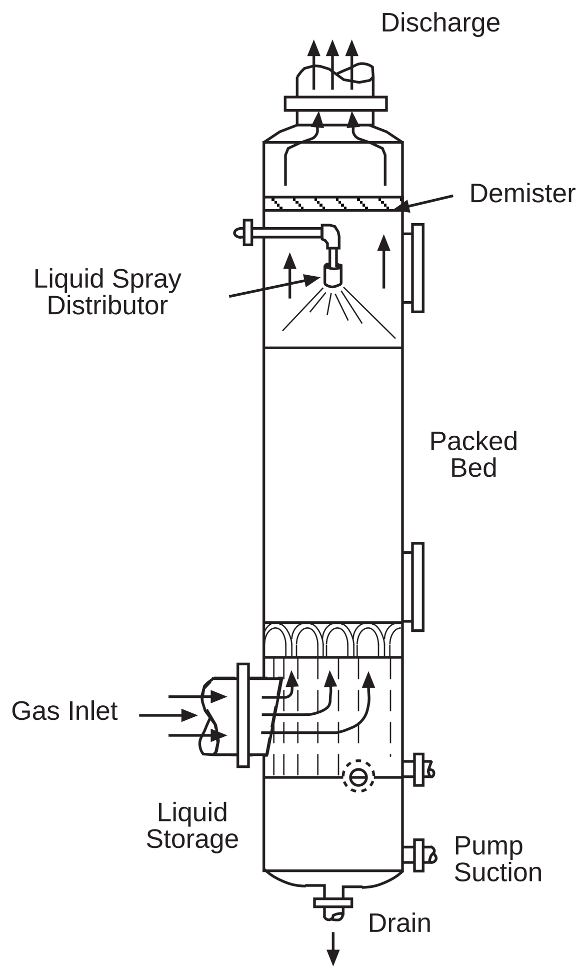


Figure 3-19. Packed bed wet scrubber.

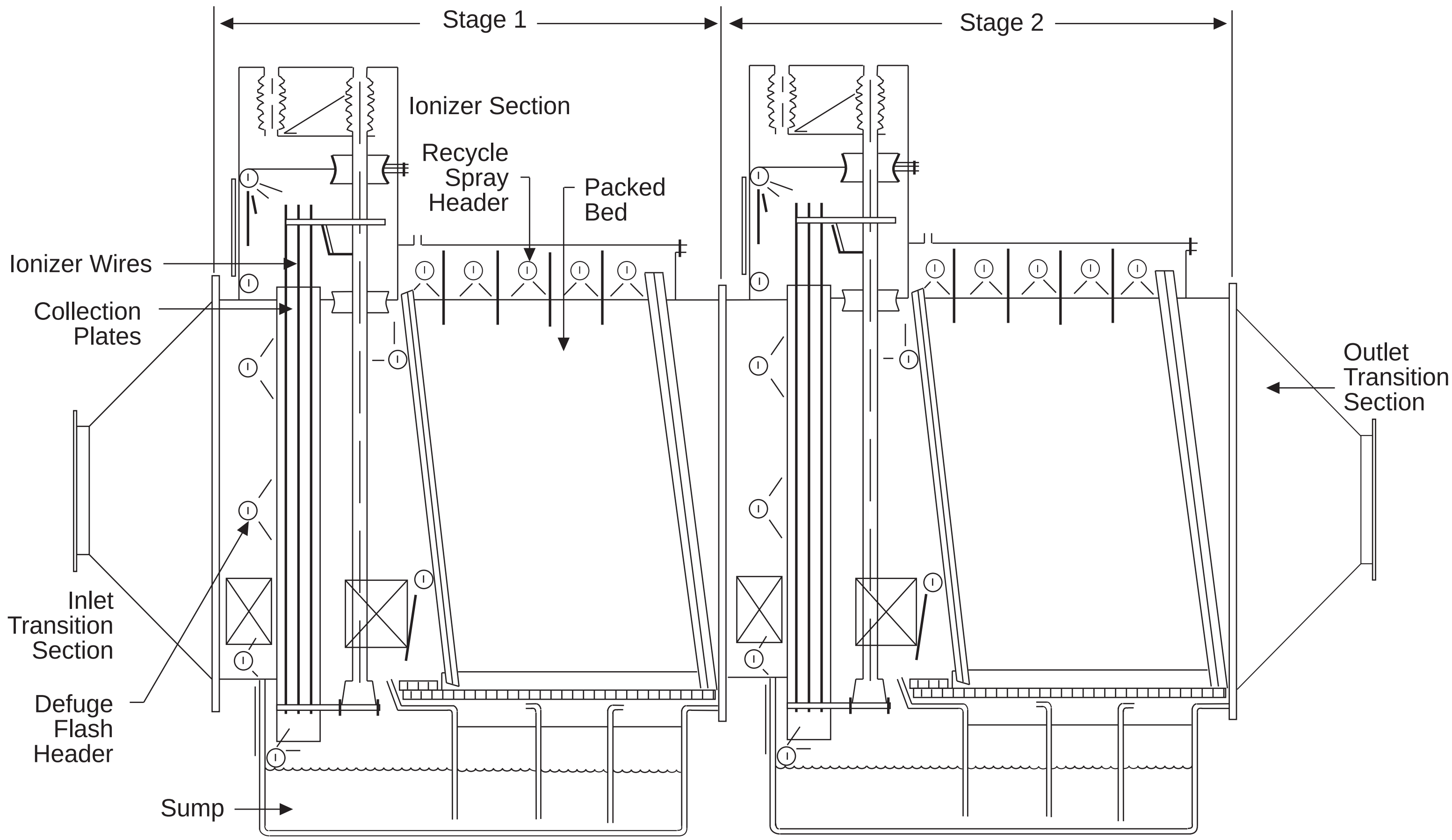


Figure 3-20. Ionizing wet scrubber schematic.

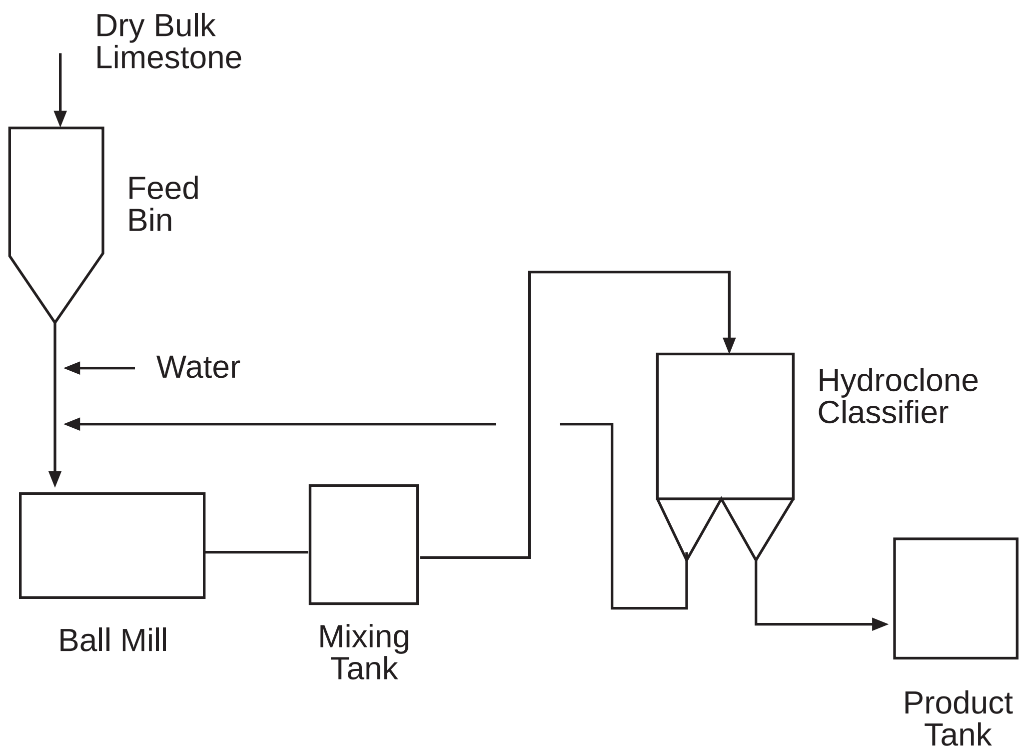


Figure 3-21. Limestone reagent preparation system for spray drying.

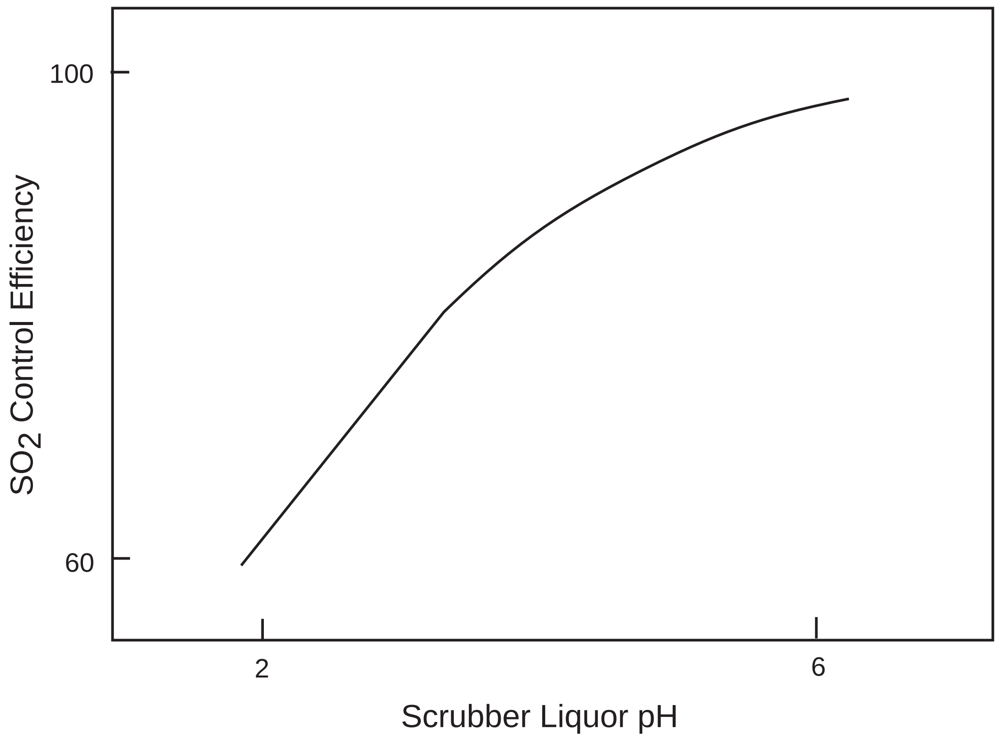


Figure 3-22. Impact of wet scrubber liquor pH on SO_2 removal efficiency.

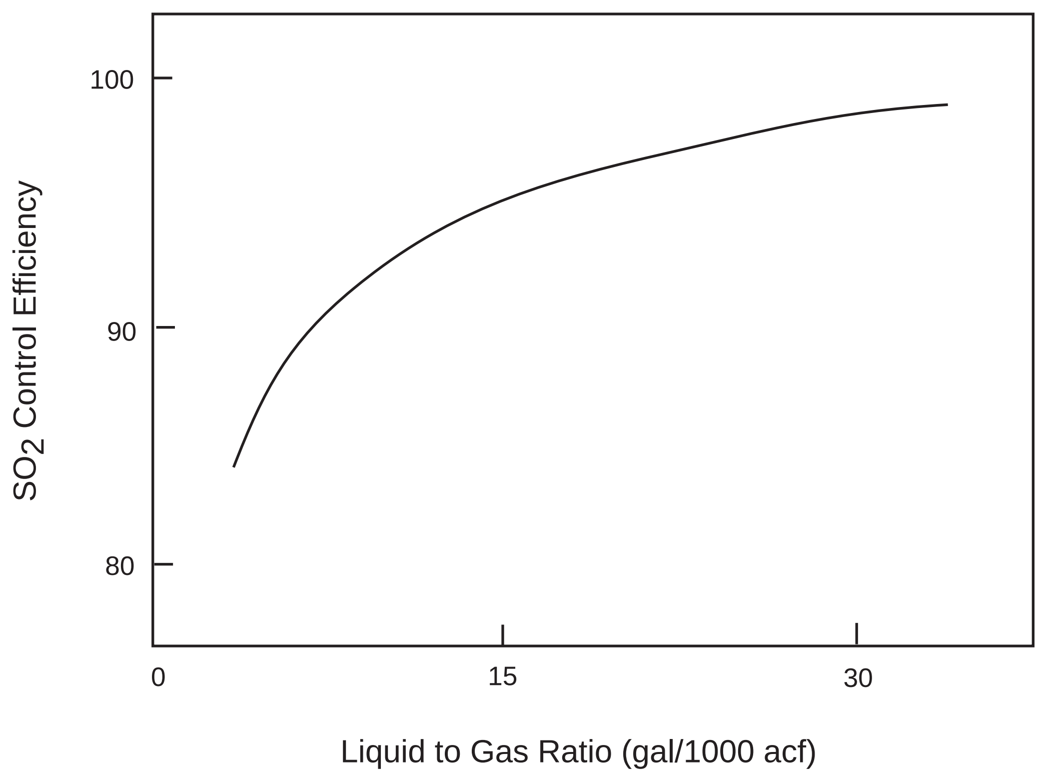


Figure 3-23. Impact of wet scrubber liquid-to-gas ratio on SO_2 removal efficiency.

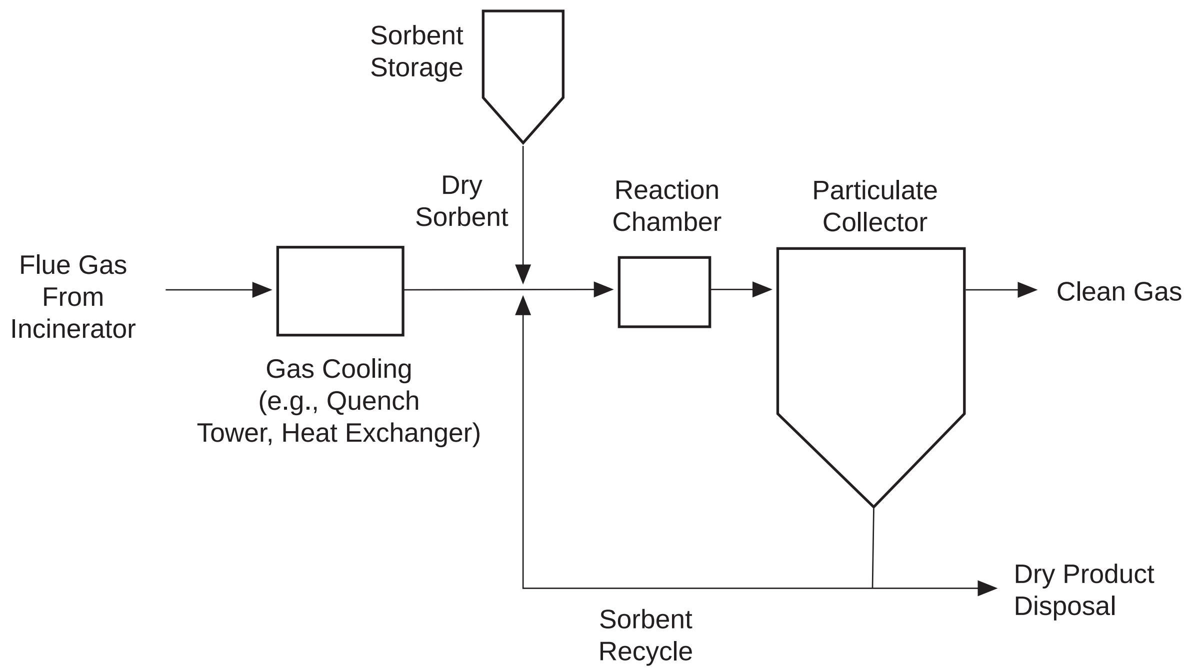


Figure 3-24. Dry scrubbing sorbent injection process schematic.

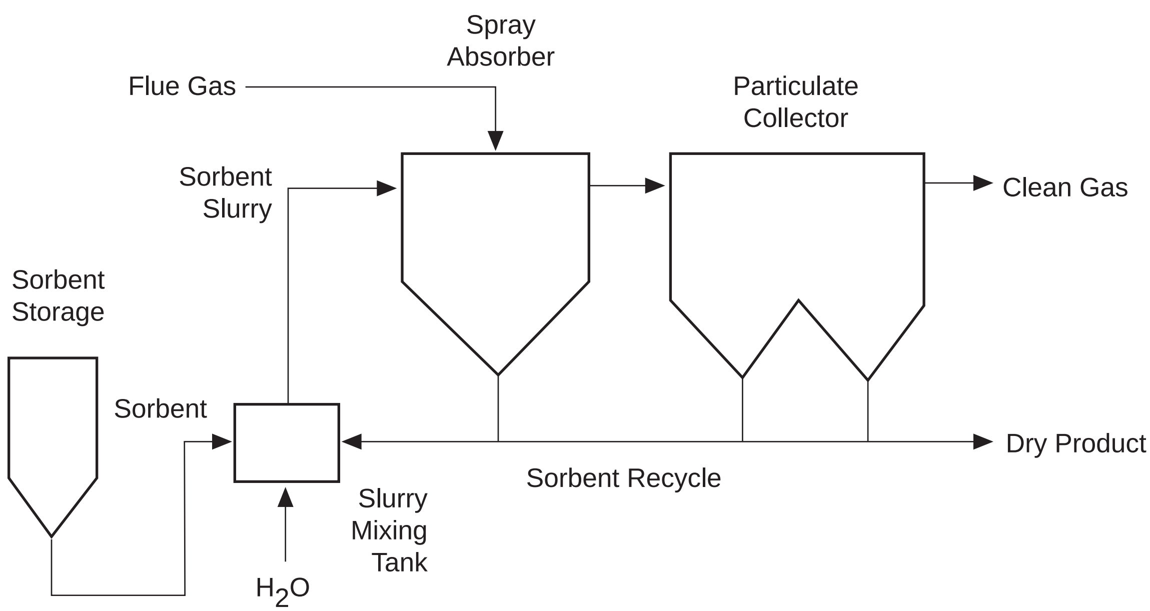
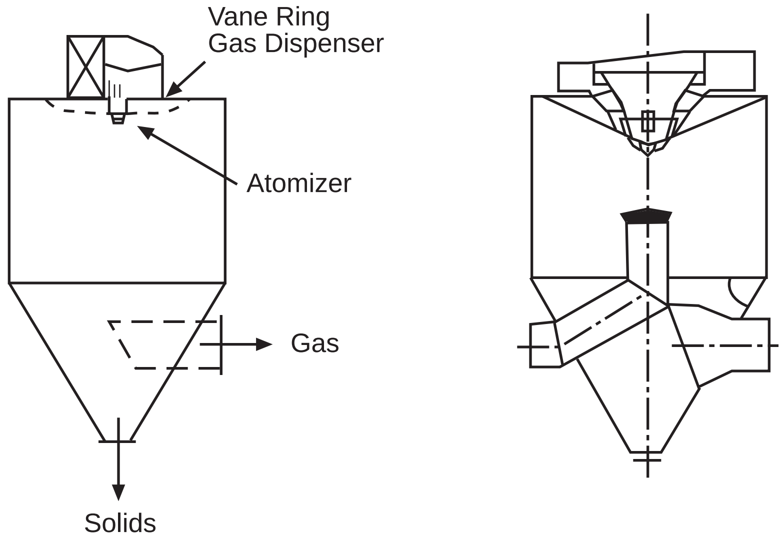
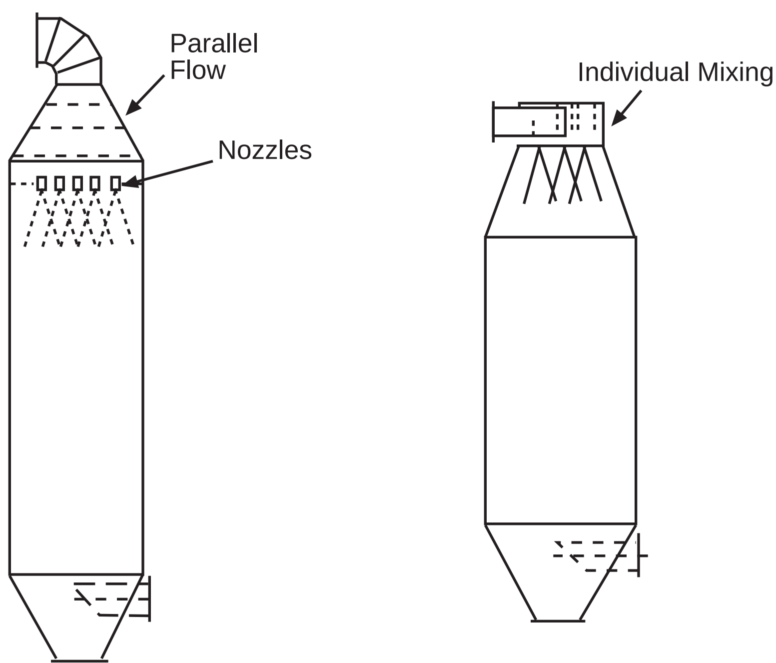


Figure 3-25. Semi-dry spray dryer absorption process schematic.



A. Rotary-Atomizer Dryers



B. Two-Fluid Pneumatic Nozzle Dryers

Figure 3-26. Spray dryer designs.

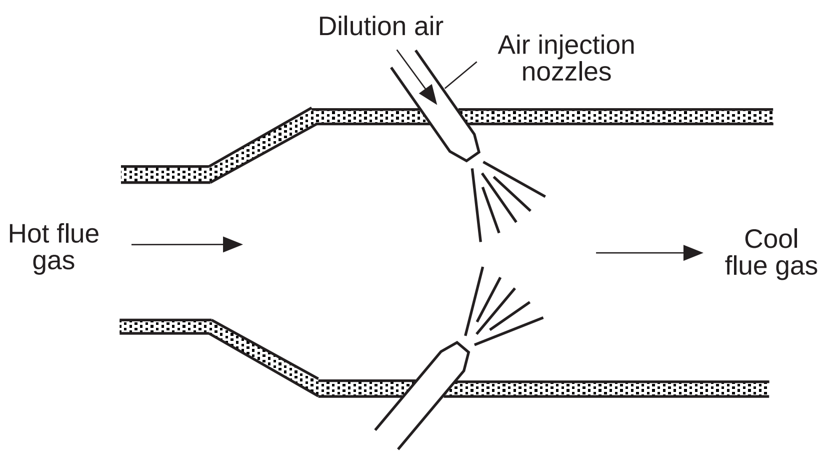
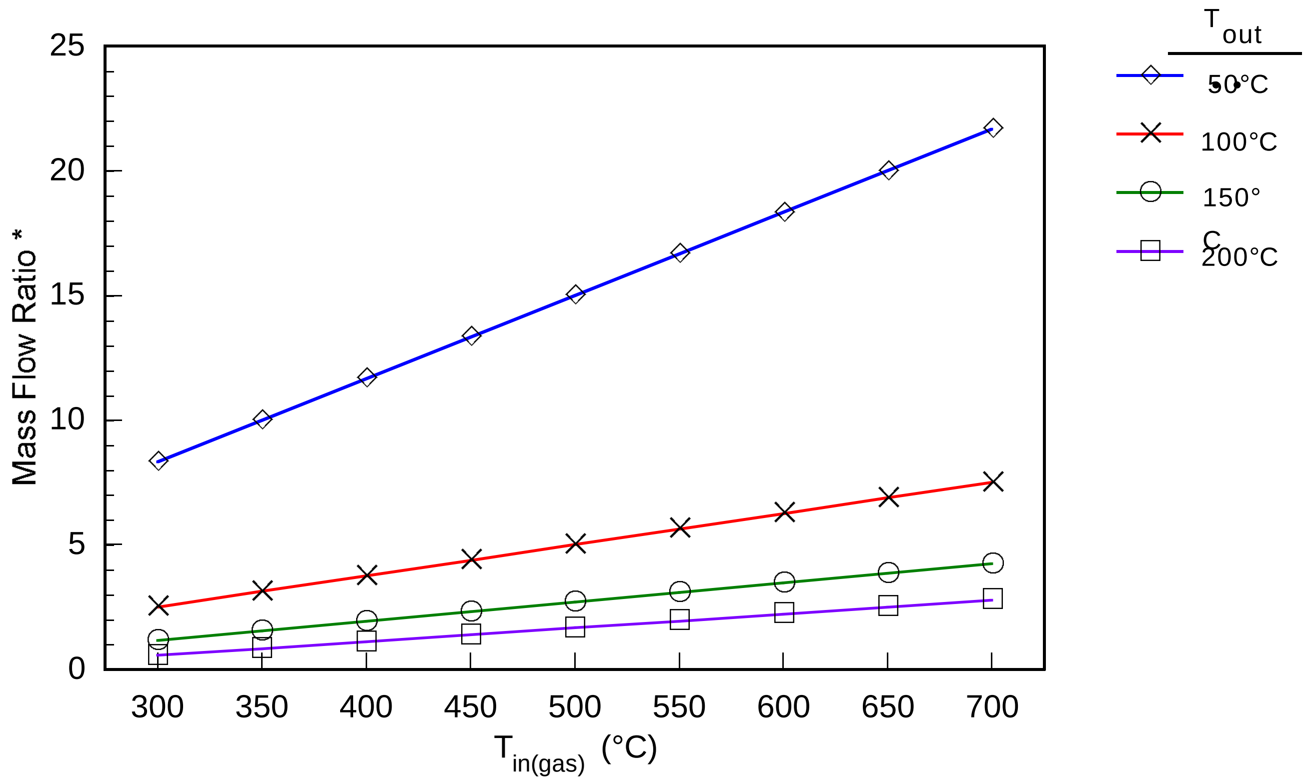
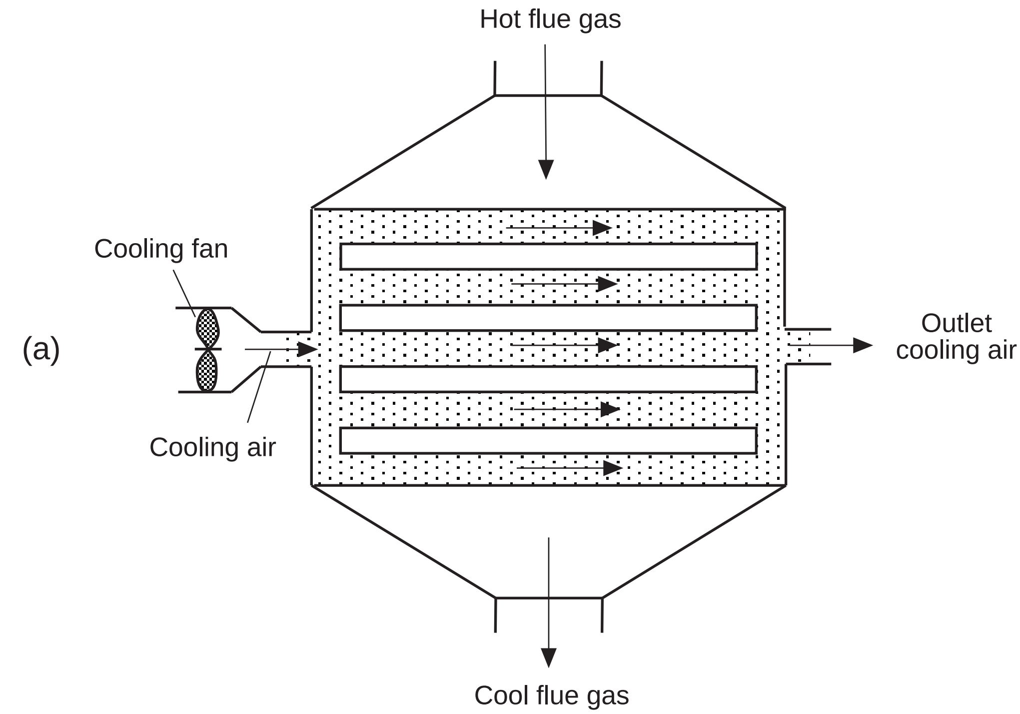


Figure 3-27. Air dilution cooling procedure.



Note: * Mass Flow Ratio = $\frac{\text{mass flow of dilution air}}{\text{mass flow of hot flue gas}}$

Figure 3-28. Example of the increase in flue gas flow rate using air dilution cooling.



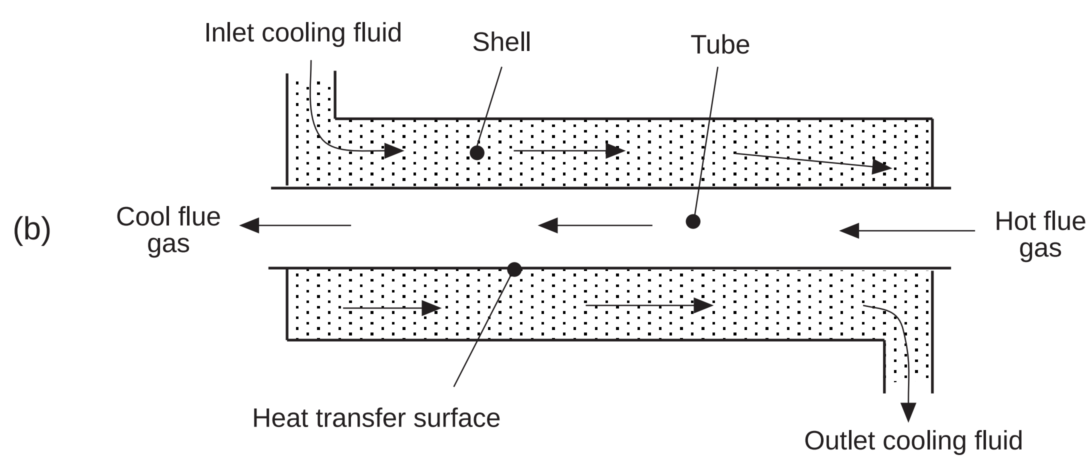


Figure 3-29. Heat exchanger schematics: (a) gas-gas recuperator; (b) shell and tube type.

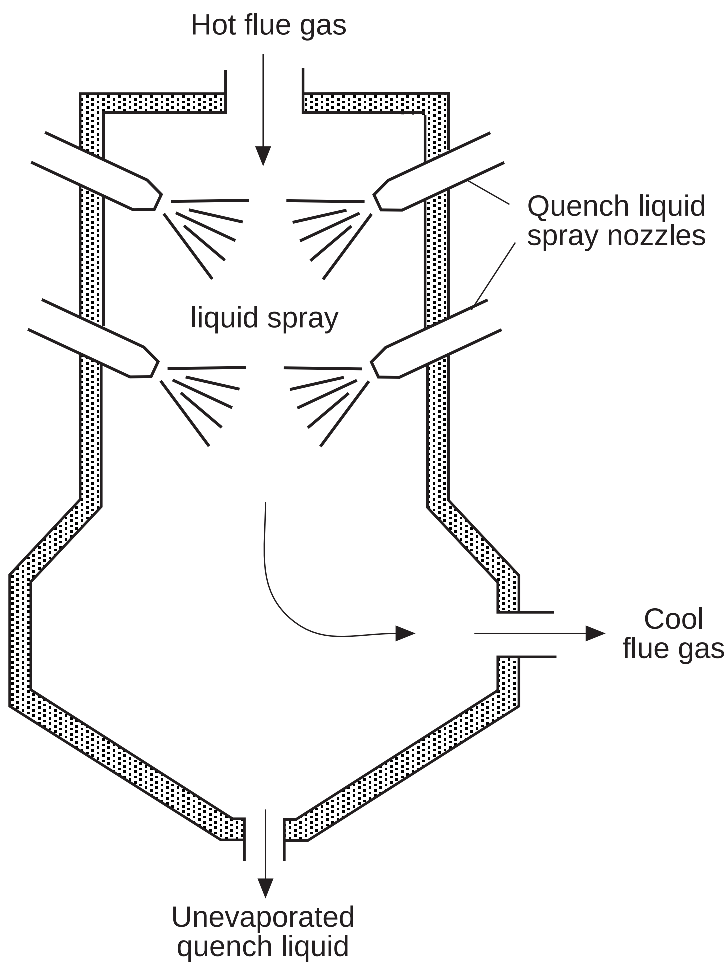
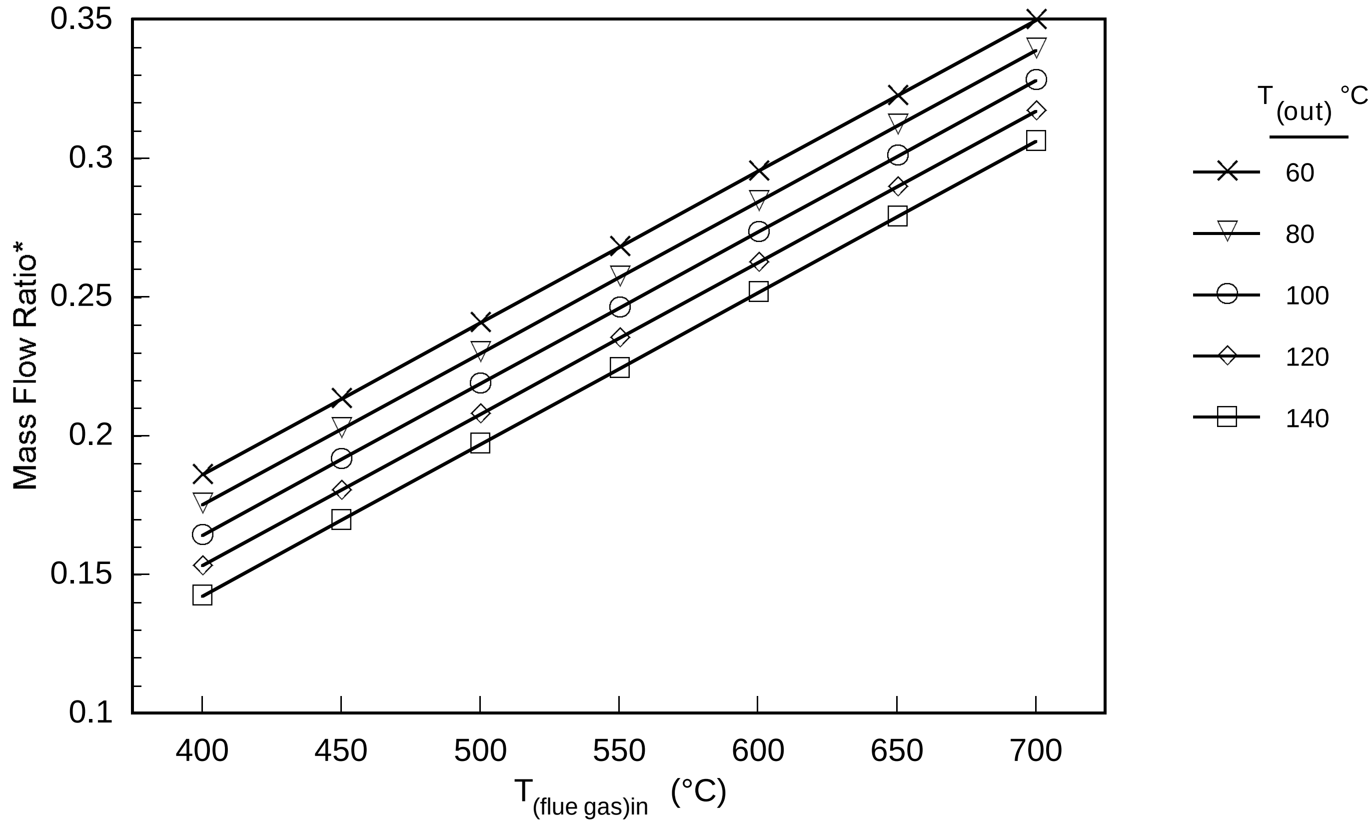


Figure 3-30. Water quench cooling procedure.



Note: * Mass Flow Ratio = $\frac{\text{mass flow of quench water}}{\text{mass flow of hot flue gas}}$

Figure 3-31. Example of increase in flue gas flow rate using water quench cooling.

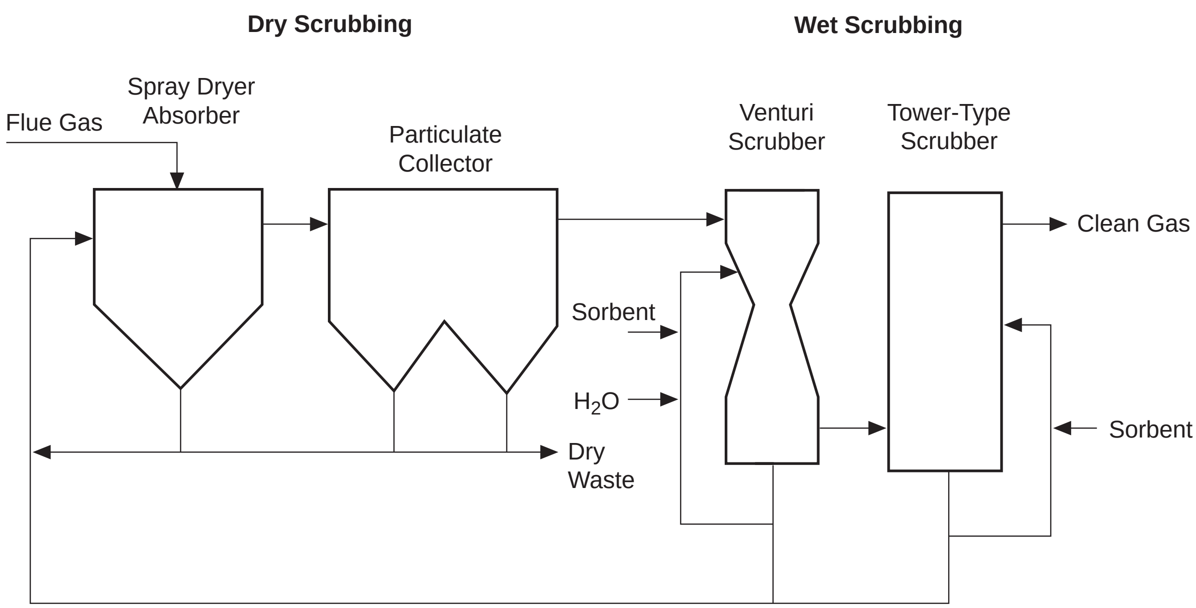


Figure 3-32. Hybrid wet/dry system schematic.

Table 3-1. Sorbents Used for Removal of Metals From Combustion Source Flue Gases

Sorbent	Primary Removal	Temperature Range (°C)	Removal Efficiency (%)
Zeolites	Hg	< 100	
Sulfur impregnated			
Activated carbon	Hg	< 200	90+
Calcium-based			
Calcium hydroxide/fly ash	Hg	< 300	
Limestone/fly ash	As, Cd, Pb	600-900	
Alumina-based	Cd, Pb	500-700	
Bauxite			
Silicates	Pb, Cd, As	600-900	
Silica sand			
Kaolinite			
Emathlite			
Aluminum silicates			

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